New Lewis-Acidic Molybdenum(II) and Tungsten(II) Catalysts for Intramolecular Carbonyl Ene and Prins Reactions. Reversal of the Stereoselectivity of Cyclization of Citronellal

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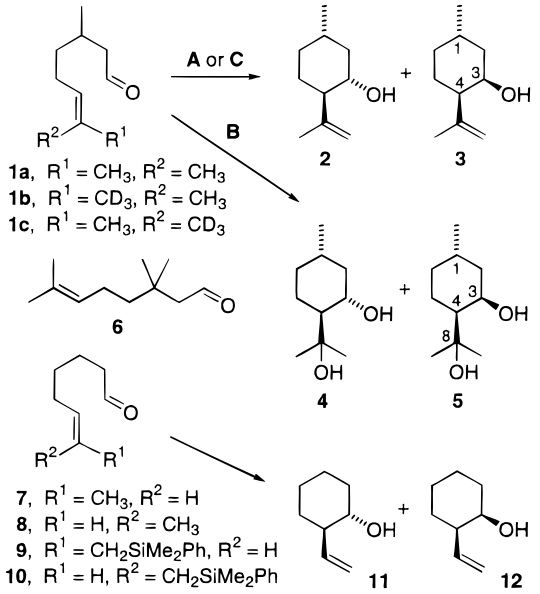
New Mo(II) complexes $BnEt_3N^+[Mo(CO)_4ClBr_2]^-$ (**A**) and $Mo(CO)_5(OTf)_2$ (**B**) and their W(II) congeners **D** and **E** have been developed as catalysts for the title reactions. Unlike other Lewis acids, the latter catalysts exhibit *cis*-stereoselectivity in the cyclization of citronellal (**1** → **3** with **A** and **1** → **5** with **B**). Isotopic labeling allowed formulation of the reaction mechanism, according to which these complexes act as bulky Lewis acids, η^1-coordinated to the carbonyl oxygen. The stereochemistry appears to be controlled by the protruding ligand L_p, which dictates the boatlike transition state **III**. The kinetically formed *cis*-alkenol **3** can be equilibrated by $[Mo(CO)_4Br_2]_2$ (**C**) or $ZnCl_2$ to its *trans*-epimer **2** via a retro-ene reaction.

Introduction

The ene reaction[1] is a powerful synthetic tool for C−C bond formation that allows construction of two vicinal chiral centers. Like the Diels−Alder addition, it proceeds thermally and can be accelerated by Lewis acids. Whereas the intermolecular ene reaction is only successful in the case of highly reactive substrates,[1,2] its intramolecular version has been extensively studied and developed into a reliable methodology.[1−3] Thus, for instance, citronellal **1a** is readily cyclized in the presence of Lewis acids ($AlCl_3$, BF_3, $SbCl_3$, $SbCl_5$, etc.; 0.1−1 equiv) to produce mainly isopulegol **2**, accompanied by its *cis*-diastereoisomer **3** (Scheme 1);[3] the **2**/**3** ratios[2,3] vary from 95:5 with ZnI_2 to 43:57 with $SbCl_5$ (Table 1, entries 1−4).[2−5] A reversal in the sense of diastereoselectivity has been observed (but not explained) for the stoichiometric reaction with $(Ph_3P)_3RhCl$, which gave a 1:3 mixture of **2** and **3** (entry 5).[6,7] Herein, we report on new molybdenum(II) and tungsten(II) catalysts, which favor formation of the

Scheme 1[a]



[a] **A** = $PhCH_2(Et)_3N^+[Mo(CO)_4ClBr_2]^-$; **B** = $Mo(CO)_5(OTf)_5$; **C** = $[Mo(CO)_4Br_2]_2$.

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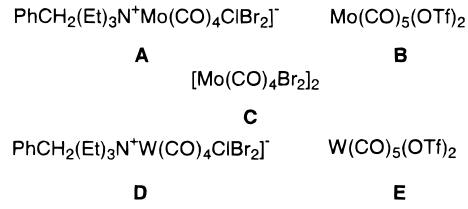
Table 1. Stereochemistry of the Carbonyl Ene/ Prins-Type Cyclization of 1, 9, and 10 with Lewis-Acid Catalysts[a]

entry	starting compd	catalyst	solvent	products	ratio *trans*:*cis*
1	**1a**	ZnI_2[b]	C_6H_6	**2** + **3**	95:5[c]
2	**1a**	$SbCl_3$[d]	C_6H_6	**2** + **3**	71:29[c]
3	**1a**	$SbCl_5$[d]	C_6H_6	**2** + **3**	43:57[c]
4	**1a**	$(TfO)_3Sc$[e]	CH_2Cl_2	**2** + **3**	80:20[e]
5	**1a**	$(Ph_3P)_3RhCl$[f]	$CHCl_3$	**2** + **3**	1:3[g]
6	**1a**	**A**	DME	**2** + **3**	25:75[h]
7	**1a**	**A**	CH_2Cl_2	**2** + **3**	40:60[h]
8	**1a**	**D**	DME	**2** + **3**	24:76[h]
9	**1a**	**B**	DME, H_2O[i]	**4** + **5**	20:80[h]
10	**1a**	**E**	DME, H_2O[i]	**4** + **5**	44:56[h]
11	**1a**	**C**[j]	DME	**2** + **3**	55:45[h]
12	**1a**	**C**[k]	CH_2Cl_2	**2** + **3**	82:18[h]
13	**9**	**A**	DME	**11** + **12**	91:9[h]
14	**9**	**B**	DME	**11** + **12**	90:10[h]
15	**10**	**A**	DME	**11** + **12**	36:64[h]

[a] At rt for 24 h with 5 mol % of the catalyst unless stated otherwise. [b] 1 equiv, 5−10 °C, 15 min. [c] See ref 3. [d] 10 mol %. [e] See refs 2a and 55. [f] 1 equiv, rt, 15 h. [g] See ref 6. [h] Established by ^{1}H NMR. [i] 1−2% H_2O. [j] 8 h. [k] 5 min.

Chart 1



cis-hydroxyalkene **3** or the *cis*-diol **5** as a result of the carbonyl ene or Prins reaction, respectively.

Results and Discussion

Carbonyl Ene- and Prins-Type Cyclization of Citronellal. Recently, we have described the utilization of molybdenum(II) and tungsten(II) complexes **A**,[8,9] **B**,[10,11] **C**,[12,13] **D**,[9] and **E**[10,11] (Chart 1) as catalysts in allylic substitution[10,12,14] and other tranformations.[8] Further investigation has now revealed their catalytic effect in the intramolecular ene-type reactions. Thus, complex **A** (5 mol %) was found to catalyze the cyclization of (±)-**1a** in dry DME (rt (room temperature), 24 h), affording a mixture of **2** and **3** in a 25:75 ratio (entry 6), from which neoisopulegol **3**[15] was isolated in 68% yield.[16] When carried out in CH_2Cl_2, the reaction was complete in 8 h (rt) and gave a 40:60 mixture of **2** and **3** (entry 7). The tungsten congener **D**[9] exhibited similar reactivity, giving **2** and **3** in a 24:76 ratio in DME (entry 8). By contrast, complex **B** (5 mol %) in wet DME preferentially produced diol **5** (73%),[17] again with a relatively high *cis*-stereoselectivity (**4**/**5** = 20:80; entry 9), and its tungsten analogue **E**[11] gave the same products (**4**/**5** = 44:56; entry 10).[18,19] Finally, a dramatic solvent effect was observed for catalyst **C**: whereas in DME a 55:45 mixture of **2** and **3** (entry 11) was formed (rt, 8 h), the reaction carried out in CH_2Cl_2 was complete in 5 min(!) and gave preferentially the *trans*- rather than *cis*-product (**2**/**3** = 82:18; entry 12), suggesting a change of mechanism. Interestingly, when the pure *cis*-product **3** was exposed to catalyst **C** in CH_2Cl_2, it was rapidly converted into a 90:10 mixture of **2** and **3** (rt, 30 min) and similar isomerization was then observed for $ZnCl_2$ and other Lewis acids.[20] This behavior indicates that the *cis*-isomer **3** results from a kinetically controlled reaction and can be equilibrated to the thermodynamically more stable *trans*-isomer **2** under the reaction conditions, which may, at least partly, take account for the differences in the stereochemistry of cyclization of **1** when various Lewis acids are employed (vide supra[3]). Although a standard axial−equatorial alcohol equilibration[1k] **3** → **2** can, a priori, rationalize this isomerization, we have been able to show that this is not the case since other axial alcohols, such as 5α-cholestan-3α-ol, are not equilibrated to their equatorial isomers under the same conditions. Therefore, a different mech-

(6) (a) Sakai, K.; Oda, O. *Tetrahedron Lett.* **1972**, 4375. (b) Funakoshi, K.; Togo, N.; Sakai, K. *Tetrahedron Lett.* **1989**, *30*, 1095. (c) Koga, I.; Funakoshi, K.; Matsuda, A.; Sakai, K. *Tetrahedron: Asymmetry* **1993**, *4*, 1857.

(7) PCC also mediates the cyclization; however, the product is instantaneously oxidized by the reagent, so that the stereochemistry of the ring closure cannot be determined: Corey, E. J.; Ensley, H. E. Suggs, J. W. *J. Org. Chem.* **1976**, *41*, 380.

(8) Šrogl, J.; Kočovský, P. *Tetrahedron Lett.* **1992**, *33*, 5991.

(9) The complex **A** was prepared from $PhCH_2(Et)_3N^+[Mo(CO)_5Cl]^-$ on bromination; see ref 8 and: (a) Ganorkar, M. C.; Stiddard, M. H. B. *J. Chem. Soc.* **1965**, 3494. (b) Abel, E. W.; Butler, I. S.; Red, J. G. *J. Chem. Soc.* **1964**, 2068. Alternatively, **A** was also obtained on the reaction of $[Mo(CO)_4Br_2]_2$ (**C**)[13] with $PhCH_2(Et_3)N^+Cl^-$. The tungsten analogue **D** was prepared according to the former protocol.

(10) (a) Dvořáková, H.; Dvořák, D.; Šrogl, J.; Kočovský, P. *Tetrahedron Lett.* **1995**, *35*, 6351. (b) Malkov, A. V.; Baxendale, I. R.; Mansfield, D. J.; Kočovský, P. *Tetrahedron Lett.* **1997**, *38*, 4895.

(11) (a) The complex **B** was generated in situ from $PhCH_2(Et)_3N^+$-$[Mo(CO)_5Cl]^-$ via a redox reaction with CF_3SO_3Ag (3 equiv) at room temperature in DME. Its tungsten congener **E** was generated in an analogous way: (b) Abbott, A. P.; Malkov, A. V.; Zimmermann, N.; Raynor, J. B.; Ahmed, G.; Steele, J.; Kočovský, P. *Organometallics* **1997**, *16*, 3690. See also ref 14a.

(12) Malkov, A. V.; Davis, S. L.; Mitchell, W. L.; Kočovský, P. *Tetrahedron Lett.* **1997**, *38*, 4899.

(13) The complex **C** was prepared by titration of $Mo(CO)_6$ with Br_2 (1 equiv) at −78 °C in a noncoordinating solvent, such as CH_2Cl_2: (a) Bowden, J. A.; Colton, R. *Aust. J. Chem.* **1968**, *21*, 2657. (b) Cotton, F. A.; Falvello, L. R.; Meadows, J. H. *Inorg. Chem.* **1985**, *24*, 514. (c) Cotton, F. A.; Poli, R. *Inorg. Chem.* **1987**, *26*, 1514. See also ref 14a.

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(15) Identical with the known compound: (a) Shishibori, T. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 1170. (b) Burkard, S.; Looser, M.; Borschberg, H.-J. *Helv. Chim. Acta* **1988**, *71*, 209.

(16) All yields refer to isolated (preparative) yields. Diastereoisomeric ratios were determined by integration of suitable signals in the ^{1}H NMR spectra of the crude product mixtures with usual accuracy (≥±2%).

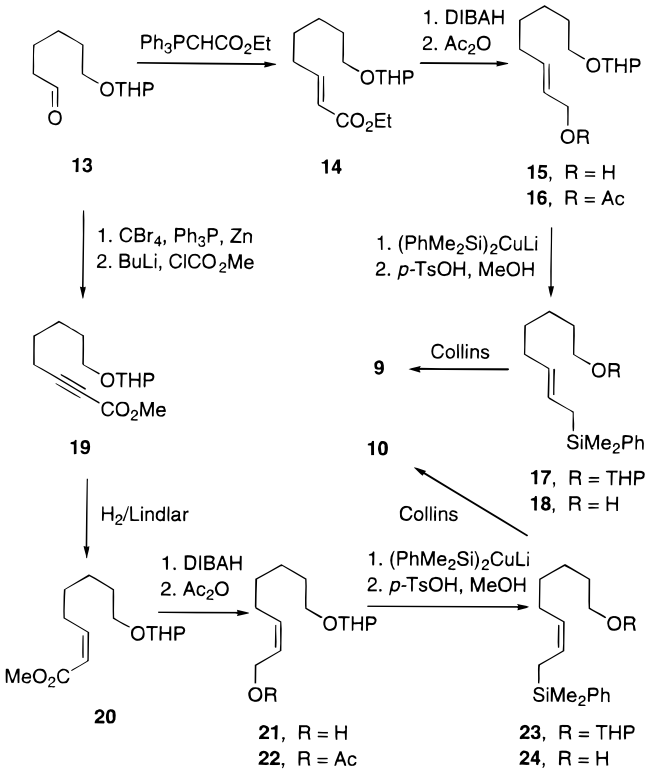
(17) The diol **5** is a plant growth inhibitor, originally isolated from *Eucalyptus citriodora*: Nishimura, H.; Nakamura, T.; Mizutani, J. *Phytochem.* **1984**, *23*, 2777.

(18) A facile, though less stereoselective, formation of the corresponding cyclopentane derivatives from 2,6-dimethyl-5-hepten-1-al has also been observed.

(19) Similar $Cp_2Ti(PMe_3)_2$-catalyzed cyclizations of 6-hepten-2-one and its congeners, leading to *cis*-disubstituted cyclopentanes, have recently been reported; attempted construction of cyclohexane homologues was, however, unsuccessful: (a) Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1995**, *117*, 6785. (b) Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 3182. (c) Kablaoui, N. M.; Hicks, F. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 5818. (d) Kablaoui, N. M.; Hicks, F. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 4424. (e) Crowe, W. E.; Rachita, M. J. *J. Am. Chem. Soc.* **1995**, *117*, 6787. (f) Crowe, W. E.; Vu, A. T. *J. Am. Chem. Soc.* **1996**, *118*, 1557. (g) Crowe, W. E.; Vu, A. T. *J. Am. Chem. Soc.* **1996**, *118*, 5508. See also: (h) Okamoto, S.; Kasatkin, A.; Zubaidha, P. K.; Sato, F. *J. Am. Chem. Soc.* **1996**, *118*, 2208. (i) Taber, D. F.; Wang, Y. *Tetrahedron Lett.* **1995**, *36*, 6639. For a review on analogous cyclization of dienes, see: (j) Buchwald, S. L.; Nielsen, R. B. *Chem. Rev.* **1988**, *88*, 1047. For related titanocene-catalyzed ene-type cycloisomerization of enynes and dienynes, see: (k) Sturla, S. J.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 1976.

(20) On the other hand, exposing **3** to either **A** or **B** (rt, ≥48 h) proved to have practically no effect, except a slow, partial decomposition/elimination.

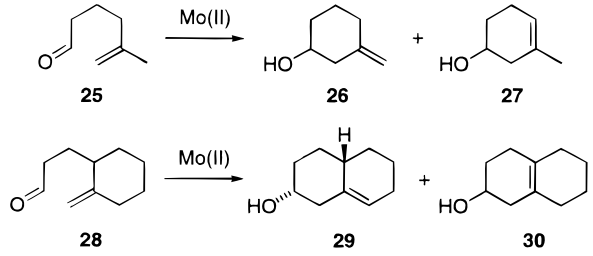
Scheme 2



anism must be operating in this system and the retro-ene reaction appears to be the most likely one.[21]

Carbonyl Ene- and Prins-Type Cyclization of Citronellal Congeners. To shed more light on the preferred formation of the *cis*-configured products on cyclization of citronellal, we prepared a series of related substrates **6**−**10**, whose cyclization in the presence of standard Lewis acids has been described previously. The methyl analogue **6** was readily obtained on cuprate addition to citral,[5a,b] and the two "demethyl" analogues of citronellal, i.e., *trans*- and *cis*-6-octen-1-al (**7**[22,23] and **8**),[22a,23] were synthesized using known methods. The synthesis of (*E*)- and (*Z*)-allylsilanes **9** and **10** commenced with the protected hydroxy aldehyde **13**, available in two steps from 1,6-hexanediol (Scheme 2). Wittig olefination of **13** with $Ph_3P{=}CHCO_2Et$ (80 °C, 3 h) afforded the α,β-unsaturated ester **14** (89%; *E*/*Z* = 96:4),[24] whose reduction with diisobutylaluminum hydride in toluene (−20 °C, 25 min) furnished allylic alcohol **15** (90%).[24a,b,25] Acetate **16**, obtained from the latter alcohol (Ac_2O, pyridine, rt, overnight; 93%), was treated with $(PhMe_2Si)_2CuLi$ (THF, −60 °C, 12 h)[26] to give allylsilane **17**

Scheme 3



(67%).[27−30] Deprotection of the latter product (**17** → **18**; *p*-TsOH, MeOH, rt, 7 h; 89%), followed by Collins oxidation, afforded the required aldehyde **9** (59%). Similar strategy was applied to the synthesis of the (*Z*)-isomer **10**: aldehyde **13**[5b] was converted in two steps into the propargylic derivative **19** (81%),[31] whose hydrogenation on Lindlar catalyst gave (*Z*)-ester **20** (99%). Diisobutylaluminum hydride reduction of the latter ester (**20** → **21**; 84%), followed by acetylation (Ac_2O, pyridine, rt), gave allylic acetate **22** (91%), which was converted into allylsilane **23** on treatment with $(PhMe_2Si)_2CuLi$ (75%).[26] Deprotection of the latter compound (*p*-TsOH, MeOH, rt; 95%), followed by Collins oxidation of the resulting alcohol **24**, afforded the desired aldehyde **10** (63%).

Surprisingly, 3-methylcitronellal (**6**) reacted very sluggishly with our catalysts (∼10% conversion over 48 h in DME)[32] and *cis*- and *trans*-6-octen-1-al (**7**, **8**) proved inert to both **A** and **B** although their ready cyclization with standard Lewis acids has been reported.[33] On the other hand, *trans*-allylsilane **9** reacted readily in the presence of either catalyst in DME, affording mixtures of the expected *trans*- and *cis*-products **11** and **12** (91:9 with **A** and 90:10 with **B**; entries 13 and 14). The *cis*-configured allylsilane **10** afforded the same product mixture with the ratio reverted in favor of *cis*-isomer **12** (64:36; entry 15), indicating the dominant control of the reaction stereochemistry exercised by the silane group rather that the catalyst.[30,34]

Other Carbonyl Ene-Type Cyclizations. Cyclization of **25**[35] (Scheme 3) is known to produce **26** on thermolysis,[35a,b] and traditional Lewis acid catalysis proceeded in a similar way.[1f] With our catalyst **A**, it afforded a mixture of regioisomers **26** and **27** in an 81:19 ratio (rt, 48 h), whereas **B** gave the same isomers in

(21) For a review on retro-ene reaction, see: Ripoll, J.-L.; Valée, Y. *Synthesis* **1993**, 659.

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(24) (a) Baldwin, S. W.; Wilson, J. D.; Aubé, J. *J. Org. Chem.* **1985**, *50*, 4432. (b) Clasby, M. C.; Craig, D.; Slawin, A. M. Z.; White, A. J. P.; Williams, D. J. *Tetrahedron* **1995**, *51*, 1509. (c) Craig, D.; Geach, N. J. *Tetrahedron: Asymmetry* **1991**, *2*, 1177.

(25) (a) Patterson, J. W. *Synthesis* **1985**, 337. (b) Martin, V. S.; Ode, J. M.; Palazon, J. M.; Soler, M. H. *Tetrahedron: Asymmetry* **1992**, *3*, 573.

(26) For a review on the synthesis of allylisilanes, see: Sarkar, T. K. *Synthesis* **1990**, 969 and 1101.

(27) For analogous Me_3Si derivatives, see refs 28 and 29; for related Bu_3Sn derivatives, see ref 30.

(28) Tietze, L. F.; Whüsch, J. R. *Synthesis* **1990**, 985.

(29) Tietze, L. F.; Schünke, C. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1731.

(30) Keck, G. E.; Dougherty, S. M.; Savin, K. A. *J. Am. Chem. Soc.* **1995**, *117*, 6210.

(31) Ma, D.; Lu, X. *Tetrahedron* **1990**, *46*, 6319.

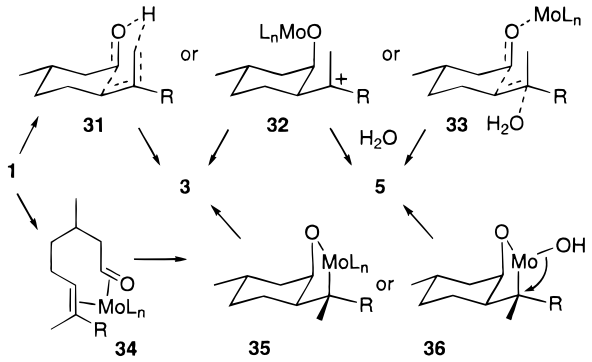
(32) With standard Lewis acids, **6** reacts readily to afford the corresponding *trans*-product.[5]

(33) Related cyclizations with $MeAlCl_2$ have been shown to lead preferentially to the *trans*-isomer, whereas Me_2AlCl tends to prefer the corresponding *cis*-isomer, which has been interpreted in terms of the differences in the relative strength of the two Lewis acids employed: (a) Snider, B. B.; Karras, M.; Price, R. T.; Rodini, D. J. *J. Org. Chem.* **1982**, *47*, 4538. For further examples of application of Me_2AlCl, see: (b) Johnson, M. I.; Kwass, J. A.; Beal, R. B.; Snider, B. B. *J. Org. Chem.* **1987**, *52*, 5419. (c) Robertson, J.; O'Connor, G.; Middleton, D. S. *Tetrahedron Lett.* **1996**, *37*, 3411.

(34) (a) Denmark, S. E.; Almstead, N. G. *J. Org. Chem.* **1994**, *59*, 5130. (b) Denmark, S. E.; Hosoi, S. *J. Org. Chem.* **1994**, *59*, 5133.

(35) (a) Albisetti, C. J.; Fisher, N. G.; Hogsed, M. J.; Joyce, R. M. *J. Am. Chem. Soc.* **1956**, *78*, 2637. (b) Viola, A.; Iorio, E. J.; Chen, K. K.; Glover, G. M.; Nayak, U.; Kocieński, J. P. *J. Am. Chem. Soc.* **1967**, *89*, 3462. (b) Wilson, R. M.; Rekers, J. W.; Packard, A. B.; Elder, R. C. *J. Am. Chem. Soc.* **1980**, *102*, 1633.

Scheme 4[a]



[a] **a**, R = CH_3; **b**, R = CD_3.

a 7:93 ratio (rt, 30 min). The former isomer **26** is apparently a kinetic product as it can be equilibrated on action of complex **B** (to give an ~1:9 **26**/**27** mixture). The analogue **28**[36] has been reported to produce a 2:3 mixture of **29** and **30** on reaction with Me_3SiCl and Mg in THF;[36] with **A** or **B**, mixtures of **29** and **30** were formed in 83:17 (rt, 48 h) and 45:55 (rt, 30 min) ratios, respectively. Again, **29** could be equilibrated in the presence of complex **B** to produce a ~1:1 **29**/**30** mixture.

This behavior suggests that our Mo(II) and W(II) complexes would catalyze cyclization of only those alkenals that are capable of fair stabilization of a positive charge, e.g., by geminal alkyl groups, as in **1**, **25**, and **28**, or owing to the β-stabilizing effect of silicon,[34] as in **9** and **10**. Other potential substrates, such as **7** and **8**, lacking these effects, are inert. Hence, the transition state must have a substantial carbocationic character,[33] with the charge developed on the sp^2 carbon (e.g., C-7 in **1**).

Mechanistic Considerations. Several mechanisms can be proposed to rationalize the cyclization of **1** (Scheme 4). Since the reaction gives rise either to an olefin (**3**) or a tertiary alcohol (**5**), carbocation **32** can be envisaged as an intermediate. Alternatively, concerted or semiconcerted processes, involving **31** or **33**, can also be considered. However, the striking preference for the *cis*-products seems to suggest a template effect, i.e., the C−C bond formation occurring in the coordination sphere of the metal (**34** → **35** or **36**),[37] followed by β-elimination (**35** → **3**) or hydration (**36** → **5**). In the former reaction, the required β-H would be available from either methyl group (**35**), so that the elimination step may not be selective. By contrast, the hydration (via **36**) should be stereospecific; i.e., the reaction should proceed as an overall *syn*-addition across the C=C bond. Similar considerations can be applied to the other pathways: thus, an overall *anti*-addition would result if the reaction proceeded via **33**, whereas a lack of, or little, stereodifferentiation can be assumed for capture of the carbocation **32**; the ene product could be formed by a regioselective deprotonation via **31**.

Labeling Experiments. Since the above considerations call for isotopic labeling, both (*E*)- and (*Z*)-isomers of d_3-labeled citronellal (±)-**1b** and (±)-**1c** were synthesized in a stereospecific manner, starting from the protected aldehyde **37**, readily obtained from the benzyl ether of citronellol via ozonization (Scheme 5).[38] Wittig olefination of the latter aldehyde with $Ph_3P{=}C(Me)CO_2Et$ (CH_2Cl_2, 40 °C, 4 h) proceeded in a remarkably stereoselective manner,[39] affording the conjugated ester **38** (93%)[40] as a 98:2 *E*/*Z* mixture. Reduction of the latter ester with $LiAlD_4$ afforded d_2-labeled alcohol **39**[41] (89%; ≥98% of d_2), which on chlorination with *N*-chlorosuccinimide and Me_2S (CH_2Cl_2, 0 °C, 5 h)[42] afforded allylic chloride **40**[43] (92%). Reduction of **40** with $LiAlD_4$ (Et_2O, reflux for 6 h) gave the d_3-derivative **41**[44] (97%; ≥98% of d_2), whose debenzylation with Li in liquid ammonia (**41** → **42**; 91%),[38,44] followed by Swern oxidation provided (*E*)-citronellal-d_3 (**1b**) (98%; ≥97% of d_3).

A prerequisite for the synthesis of the (*Z*)-isomer **1c** was a stereoselective access to the (*Z*)-isomer of ester **38**, which would allow us to employ the same strategy for the isotopic labeling. After considering the suitability of several approaches, we chose one that relies on deprotonation of the intermediate in Wittig olefination.[45] According to this strategy, aldehyde **37** was treated with the ylide obtained from $Ph_3P^+CH_2CH_3\ Br^-$ and *n*-BuLi (THF, −78 °C, 5 min). The betaine intermediate thus generated was deprotonated with 1 equiv of *n*-BuLi (THF, −78 to 0 °C), and the resulting anion was treated with paraformaldehyde (0 °C, 1 h, then rt, 10 h)[45] to afford allylic alcohol **43** (45%) as a 93:7 mixture of (*Z*) and (*E*) isomers.[46] The latter allylic alcohol was first oxidized with MnO_2 to the corresponding aldehyde (0 °C, 30 min; 98%), which was then treated with MnO_2, NaCN, and AcOH in MeOH (rt, 12 h); in this mixture, the in situ generated cyanohydrin was oxidized by the present MnO_2 to the corresponding α-ketoacid nitrile,[47] methanolysis of which gave rise to the required (*Z*)-ester **44** (48%). Reduction of **44** with $LiAlD_4$ followed by replacement of the allylic hydroxyl with chlorine[42] (**44** → **45** → **46**) and another reduction with $LiAlD_4$ afforded d_3-derivative **47** (88%

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(37) Related C−C bond forming cyclizations with the prerequisite coordination of C=O and C=C to a transition metal have been reported for Rh, W, and Ti. Rh: (a) Fairlie, D. P.; Bosnich, B. *Organometallics* **1988**, *7*, 936. (b) Fairlie, D. P.; Bosnich, B. *Organometallics* **1988**, *7*, 946. W: (c) Bryan, J. C.; Arterbun, J. B.; Cook, G. K.; Mayer, J. M. *Organometallics* **1992**, *11*, 3956. Ti: refs 19a−h. For stable complexes having C=O and C=C coordinated to Mo(0) or W(0), see, e.g.: (d) King, R. B. *J. Organomet. Chem.* **1967**, *8*, 139. (e) Schmidt, T.; Krüger, C.; Betz, P. *J. Organomet. Chem.* **1991**, *402*, 97.

(38) (a) Overman, L. E.; Jacobsen, E. J. *J. Am. Chem. Soc.* **1982**, *104*, 7225. (b) Kim, M. Y.; Starrett, J. E.; Weinreb, S. M. *J. Org. Chem.* **1981**, *46*, 5383. (c) Breitenbach, R.; Chiu, K.-F.; Massett, S. S.; Meltz, H.; Muritiashan, C. W. *Tetrahedron: Asymmetry* **1996**, *7*, 435.

(39) Coates, R. M.; Ley, D. A.; Cavender, P. L. *J. Org. Chem.* **1978**, *43*, 4915.

(40) Kocieński, P. J.; Pritchard, M.; Wadman, S. N.; Whitby, R. J.; Yeates, C. L. *J. Chem. Soc., Perkin Trans. 1* **1992**, *1*, 3419.

(41) For the unlabeled product, see: (a) Umemura, T.; Mori, K. *Agric. Biol. Chem.* **1987**, *51*, 217. (b) Phandis, A. P.; Sinha, B.; Nanda, B.; Patwardhan, S. A.; Rao, J. V.; Sharma, R. N. *Monatsh. Chem.* **1989**, *120*, 581.

(42) For the method, see: Corey, E. J.; Kim, C. U.; Takeda, M. *Tetrahedron Lett.* **1972**, 4339.

(43) For the unlabeled product, see ref 41a and the following: Mori, K.; Umemura, T. *Tetrahedron Lett.* **1981**, *22*, 4429.

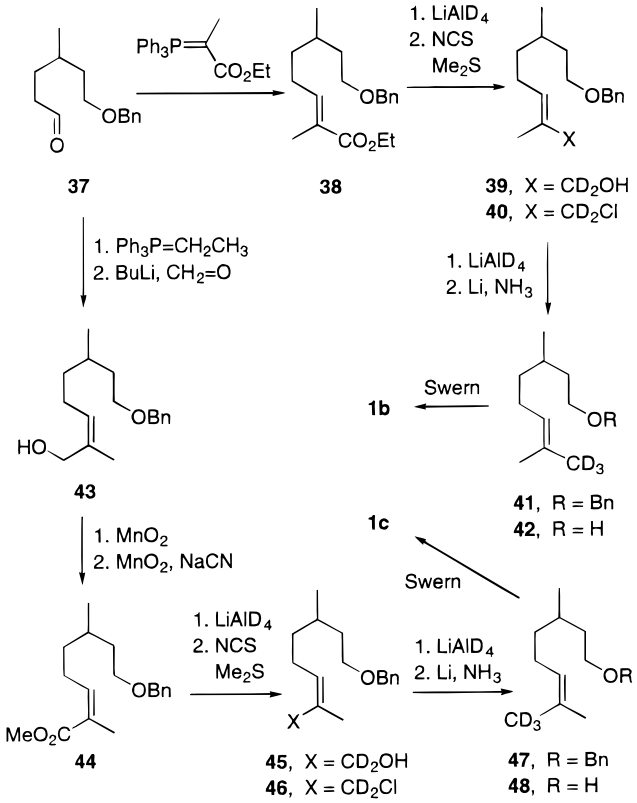
(44) For the unlabeled product, see refs 38a,b and the following: Patel, D. V.; Van Middlesworth, F.; Donaubauer, J.; Gannett, P.; Sih, C. J. *J. Am. Chem. Soc.* **1986**, *108*, 4603.

(45) For the method, see: (a) Corey, E. J.; Yamamoto, H. *J. Am. Chem. Soc.* **1970**, *92*, 226. (b) Corey, E. J.; Yamamoto, H.; Herron, D. K.; Achiwa, K. *J. Am. Chem. Soc.* **1970**, *92*, 6635. (c) Corey, E. J.; Yamamoto, H. *J. Am. Chem. Soc.* **1970**, *92*, 6637. (d) Schlosser, M.; Christmann, K.-F. *Justus Liebigs Ann. Chem.* **1967**, *708*, 1. (e) Schlosser, M.; Christmann, K.-F.; Pískala, A. *Chem. Ber.* **1970**, *103*, 2814.

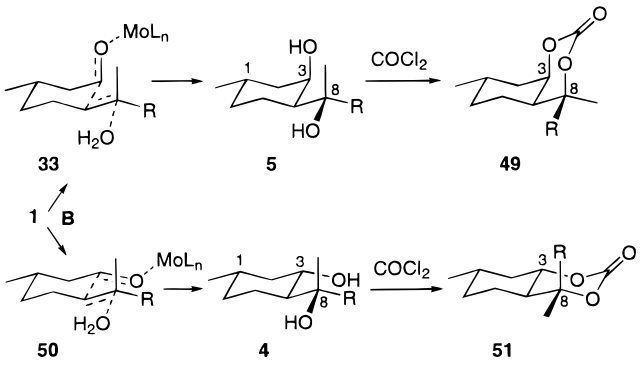
(46) Allylic oxidation in these and related systems is less selective: (a) Bhalerao, U. T.; Rapoport, H. *J. Am. Chem. Soc.* **1971**, *93*, 4835. (b) McMurry, J. E.; Kočovský, P. *Tetrahedron Lett.* **1984**, *25*, 4187.

(47) For the method, see: Corey, E. J.; Katzenellenbogen, J. A.; Gilman, N. W.; Roman, S.; Erickson, B. W. *J. Am. Chem. Soc.* **1968**, *90*, 5618.

Scheme 5



Scheme 6[a]

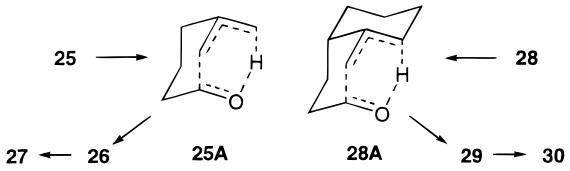


[a] **a**, R = CH_3; **b**, R = CD_3.

overall), whose deprotection (Li, NH_3; 84%) followed by Swern oxidation led to (*Z*)-citronellal-d_3 (**1c**) (92%; ≥97% of d_3).

Treatment of **1b** with **B** (5 mol %) in wet DME afforded the expected 1:4 mixture of *trans*- and *cis*-diols **4b** and **5b**; the latter diol proved to be an 85:15 mixture of the C-8 epimers[48] (Scheme 6). To determine the configuration at C-8 of **5b**, the latter product was converted into the anancomeric carbonate **49b** on reaction with phosgene ($COCl_2$, toluene, pyridine, 0 °C, 15 min, 93%). In the ^{1}H NMR spectrum of its nondeuterated congener **49a**, prepared from **5a** in the same manner, the geminal methyls appeared as singlets at 1.38 (equatorial CH_3) and 1.51 (axial CH_3) ppm, respectively. The latter group exhibited a significant NOE with 3-H (d at 4.85) in the spectrum of **49a**, and the same effect was observed for **49b**. Furthermore, the singlet at 1.38 ppm was substantially reduced in the spectrum of **49b** (giving, again, an 85:15 epimeric ratio). Therefore, the configuration at C-8 in **49b** and, consequently, in **5b** must be (*S**) as shown (for the main epimer). The configuration at C-8 of the *trans*-diol **4b**, arising as the minor product, was established in the same way, i.e., via comparison of the ^{1}H NMR spectra of the corresponding carbonates **51a**,**b**: in the spectrum of **51a**, signals for the geminal methyls appeared at 1.30 (axial CH_3) and 1.37 (equatorial CH_3) ppm, respectively, as revealed by an NOE effect of the former with 3-H (dt at 4.13 ppm); in the spectrum of **51b**, the signal at 1.30 ppm was substantially reduced. These results are consistent with the preferential *anti*-addition across the C=C bond (**1** → **33** → **5** for the major product and **1** → **50** → **4** for its isomer), i.e., with the Prins reaction mechanism.

Scheme 7



In light of the mechanism of the Prins-type cyclization **1** → **5** discused above, formation of the ene-type product **3** from **1**, catalyzed by **A** (Scheme 4), can be viewed as proceeding via **31** (rather than **35**). In the case of **1b**, the elimination occurs from CH_3 and CD_3 in a 70:30 ratio (i.e., preferentially via **31b**), as revealed by the relative intensities of the signals corresponding to the vinylic and C*H*OH protons in the ^{1}H NMR spectrum of the product. This ratio mainly reflects the kinetic isotope effect as shown by comparison with the reactivity of the (*Z*)-isomer **1c**, which gave a 64:36 mixture. With less bulky reagents, a proton is known to be removed selectively from Me_E (**1** → **2**).[5b]

In the case of substrates **25** and **28** (Schemes 3 and 7), the proton abstraction is fairly regioselective, preferentially giving the expected products of formal ene reaction **26** and **29**, respectively, on treatment with **A**. In fact, Marshall has shown by stereospecific deuteration that cyclization of **25** with traditional Lewis acids occurs with a 95:5 preference for the intramolecular proton transfer (via **25A**).[1h] Formation of **29** from **28** in the presence of catalyst **A** also suggests an intramolecular abstraction, namely that of an axial proton (**28A**), favored over the equatorial deprotonation as a manifestation of the stereoelectronic effect. By contrast, catalysis with complex **B** led mainly to the regioisomers **27** and **30**, respectively, which can be attributed to isomerization of the kinetic products **26** and **29**. Control experiments lend credence to this rationalization as both **26** and **29** can be equilibrated on treatment with catalyst **B** (vide supra).

Mechanistic Epilogue. These experiments indicate that all the complexes **A**−**E** act as Lewis acids. In accord with the behavior of other catalysts of this class, **A**−**E** can be assumed to operate via the corresponding η^1-complexes with the usual *trans*-geometry[30,34,49] of the C=O bond (Chart 2). Two chairlike transition states *trans*-TS‡ **I** and *cis*-TS‡ **II** and a boatlike *cis*-TS‡ **III**, all with

(48) The epimeric ratio was determined by integration of the geminal CH_3 signals in the ^{1}H NMR spectrum.

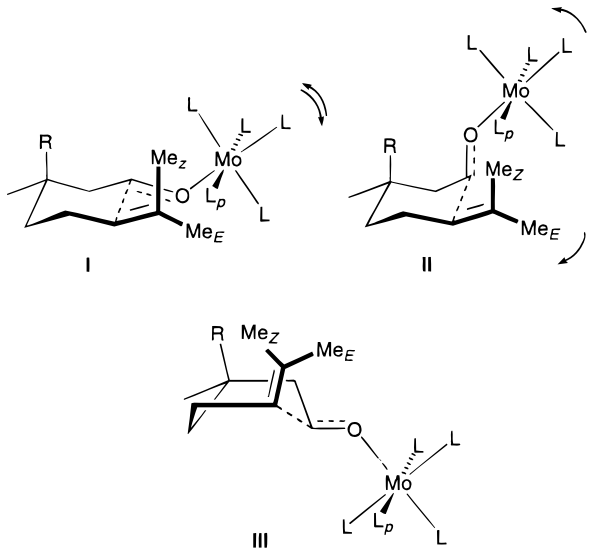
(49) (a) Denmark, S. E.; Weber, E. J.; Wilson, T. M.; Wilson, T. M. *Tetrahedron* **1989**, *45*, 1053. See also: (b) Thiyagarayan, B.; Michalczyk, L.; Bollinger, J. C.; Huffman, J. C.; Bruno, J. W. *Organometallics* **1996**, *15*, 1989 and references therein. (c) Seebach, D.; Goliński, J. *Helv. Chim. Acta* **1981**, *64*, 1413.

the preferred synclinal disposition of the π-systems,[49] can be envisioned.[50] In *trans*-TS‡ **I**, a severe repulsive interaction can be identified between the proximal ligand L_p and the geminal methyl groups Me_E and Me_Z;[51] note that L_p cannot be easily relieved from its wedged-in position by rocking (see the arrows). The *cis*-TS‡ **II** is not free of steric congestion either although the repulsive interaction between L_p and Me_Z can partly be released by bending, as suggested by the arrows. In the instance of **6** (R = Me), the additional methyl group would impose a 1,3-diaxial interaction with the O[M] group (**II**), which can account for the lack of reactivity of **6**. However, the *cis*-TS‡ **II** still seems to be too congested due to the clash between Me_Z and L_p. A third possibility is the boatlike TS‡ **III**, in which the latter obstacle is avoided. Inspection of this model shows the methyl group of **1** (R = H) in an equatorial position, whereas in the case of **6** (R = Me) the additional methyl has to assume an inconvenient axial position so that this model can also rationalize the lack of the accelerating effect of the geminal dimethyl. The boatlike TS‡ **III** gains further credence from a recent study by Brown,[1j] who has demonstrated by isotopic labeling that, while sterically nondemanding Lewis acids (e.g., Me_2AlCl) react via a chairlike TS‡, extremely bulky Lewis acids, such as Yamamoto's MABR, tend to prefer a boatlike TS‡ (rather than the originally proposed[52] "open" mechanism) if this is the best way to avoid unfavorable steric interactions between the substituents and the metal ligands. We believe that our complexes **A**, **B**, **D**, and **E** belong to this category owing to L_p.[53]

(*E*)-Allylsilane **9**, lacking the Me_Z group, is readily cyclized to give the *trans*-product **11**, presumably via a *trans*-TS‡ similar to **I**. On the other hand, (*Z*)-allylsilane **10**, lacking the Me_E group, was found to produce mainly the *cis*-isomer **12**, presumably via a *cis*-TS‡ similar to **II**. Apparently, the reactivity of these activated ene substrates is mainly controlled by the secondary orbital interaction as proposed by Denmark.[34,49a]

It may be argued that the stereochemistry of the cyclization is dependent on the strength of the Lewis acid employed and, consequently, on the magnitude of the charge being developed in the transition structures. The negative oxygen would then stabilize the partial positive charge on the olefinic component.[54] However, the latter stabilization can apply to all synclinal arrangements in the transition states **I**−**III** so that this effect alone can hardly be responsible for the observed variations. Moreover, the 43:57 *trans*/*cis* ratio (Table 1, entry 3) obtained with $SbCl_5$ (itself a strong Lewis acid)[3] demonstrates the importance of the steric effects and so does the recent report by Brown on the boatlike transition state (vide supra).[1j] Finally, comparison of the Mo(II) complexes **A** and **B** with **C** lends further credence to the steric argument: while **A** and **B** carry strongly coordinating ligands, of which one can easily assume the role of the protruding L_p (Chart 2), **C** is known to shed one or two of its CO ligands in weakly coordinating solvents (presumably due to the *trans*-effect of the bromine atoms), such as THF.[13] Hence, complex **C** may actually lose its L_p ligand and, as a result, can be anticipated to behave similarly to the sterically less demanding Lewis acids, i.e., to produce *trans*-isomer preferentially. The experimental results (vide supra) are fully compatible with this hypothesis. Therefore, it can be concluded that the degree of congestion in the transition states **I**−**III**, which is dependent on the Lewis acid employed, is the main factor controlling the stereochemistry of the ene-type cyclization rather than the strength of the Lewis acid: whereas the bulky Rh(I)[6] and our Mo(II) and W(II) complexes appear to favor *cis*-TS‡ **III**, the relatively small reagents ($ZnCl_2$, $AlCl_3$, BF_3, etc.[3]), lacking the protruding L_p-type ligand, prefer *trans*-TS‡ **I**, and $SbCl_5$ (hexacoordinate!)[3] shows slight preference for the *cis*-isomer. Particularly convincing is the comparison between $SbCl_3$ and $SbCl_5$, where the shift from *trans*- to *cis*-product is notable (compare entries 2 and 3 in Table 1).[55] The retro-ene equilibration (vide supra) may further contribute to the usually observed preference for **2** in the case of strong Lewis acids.

Chart 2[a]



[a] R = H or CH_3; L = CO or Br.

Conclusions

In conclusion, we have designed new Mo(II) catalysts **A**−**C**, which induce intramolecular cyclization of olefinic

(50) The highest observed *trans*/*cis* ratio 20:80 corresponds to ~1 kcal·mol^{-1} energy difference between **I** and **II**/**III** (at room temperature).

(51) Similar steric effect of a protruding CO ligand has been reported for the Diels−Alder addition of dienes to vinylmetallocarbenes, where it attenuates the secondary orbital interactions: Powers, T. S.; Jiang, W. Q.; Su, J.; Wulff, W. D. *J. Am. Chem. Soc.* **1997**, *119*, 6438−6439.

(52) (a) Maruoka, K.; Ooi, T.; Yamamoto, H. *J. Am. Chem. Soc.* **1990**, *112*, 9011. (b) Maruoka, K.; Saito, S.; Ooi, T.; Yamamoto, H. *Synlett* **1991**, 579. (c) Ooi, T.; Maruoka, K.; Yamamoto, H. *Tetrahedron* **1994**, *50*, 6505.

(53) (a) In the case of transition metals, alternative η^2-coordination to C=O cannot be, a priori, ruled out, although group 6 complexes, as a rule, prefer η^1-coordination. Inspection of the corresponding models for transition states with η^2-coordination shows much less dramatic differences than those identified for **I**−**III** (i.e., with η^1-coordination). (b) For an excellent review on the modes of coordination of carbonyl groups to various transition metals (i.e., η^1 vs η^2), see: Shambayati, S.; Crowe, W, E.; Schreiber, S. L. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 256. (c) For recent, clear-cut examples of η^1 vs η^2 coordination of an aldehyde group, see: Lenges, C. P.; Brookhart, M.; White, P. S. *Angew. Chem., Int. Ed.* **1999**, *38*, 552.

(54) This effect has been proposed to rationalize the predominant formation of the *cis*-product on cyclization cyclization of citronellal in micelles: Clark, B. C., Jr.; Chamblee, T.; Iacobucci, G. A. *J. Org. Chem.* **1984**, *49*, 4557.

(55) Preferential formation of the *trans*-isomer (**2**/**3** = 80:20 at room temperature and 94:6 at −78 °C) has recently been reported for $(TfO)_3Sc$ in CH_2Cl_2;[2a] we have observed an 80:20 ratio with $(TfO)_3Yb$ (rt, CH_2Cl_2).

aldehydes. In the case of citronellal (**1**) as a prototype substrate, preferential formation of the kinetic products with the *cis*-configuration at the newly formed chiral centers was observed. These catalysts are more efficient than those in existence (≤5 mol % is sufficient) and can be tuned to drive the reaction either toward the ene- or Prins-type product (**3** or **5**). Our experiments shed light on the mechanism and show that formation of a *cis*-product in reactions such as these may not always involve a C−C bond formation occurring on the metal template. Moreover, the crucial role of the protruding ligand L_p on the stereochemical outcome has been demonstrated; in conjunction with Wulff's report,[51] it appears that these effects play a more important role in the reactivity of transition metal complexes than previously realized. Finally, the switch from the chairlike to the boatlike[1j] mechanism (**III**) can be a viable option. In view of the crowded TS‡, asymmetric induction due to a chiral ligand effect can be envisioned.

Experimental Section

General Procedure. Melting points were determined on a Kofler block and are uncorrected. The IR spectra were recorded in $CHCl_3$ (or $CDCl_3$) unless stated otherwise. The NMR spectra were recorded for $CDCl_3$ solutions at 25 °C on 250 or 300 MHz instruments. The coupling constants were obtained by first-order analysis. The mass spectra were measured using direct inlet and the lowest temperature enabling evaporation or in a thermospray mode; chemical ionization was used in certain cases (with NH_4). GC analysis was carried out using capillary columns (BP10 25 m × 2.65 μm). All reactions were carried out under nitrogen. The identity of labeled compounds was established by comparison of their spectral data with those published for the unlabeled analogues or obtained for authentic, unlabeled samples. Yields are given for isolated product showing one spot on a chromatographic plate and no impurities detectable in the NMR spectrum.

Typical Procedure for the Ene-Type Cyclization (Procedure I). To a solution of dry catalyst **A** (5 mol %) in DME (1 mL) was added a solution of citronellal **1a** (154 mg, 1.0 mmol) in DME (1 mL). The resulting yellow solution was stirred at room temperature for 24 h and then diluted with ether and washed with saturated aqueous solution of $NaHCO_3$ and brine. The combined organic layers were dried with $MgSO_4$ and filtered through a pad of silica gel to remove inorganic residues. The solvent was evaporated under reduced pressure, and the residue was chromatographed on a column of silica gel with a petroleum ether−ether mixture (9:1) to afford neoisopulegol (**3a**) (105 mg, 68%) as a colorless oil, whose spectral data correspond to those described in the literature:[15] IR ν 1650, 2900, 3560 cm^{-1}; ^1H NMR δ 0.91 (d, J = 6.4 Hz, 3 H, CH_3CH), 1.81 (s, 3 H, CH_3C=CH_2), 4.03 (br d, J = 2.3 Hz, 1 H, CH−OH), 4.81 (s, 1 H, C=CHH), 4.98 (s, 1 H, C=CHH); ^{13}C NMR δ 22.30 (q), 22.75 (q), 23.92 (t), 25.79 (d), 34.74 (t), 40.89 (t), 48.37 (d), 66.28 (d), 111.23 (t), 147.27 (s). Continued elution furnished isopulegol (**2a**) (17 mg, 11%), whose ^1H NMR spectrum was identical with that of an authentic sample obtained from Fluka: ^1H NMR δ 0.86 (d, J = 6.6 Hz, 3 H, CH_3CH), 1.71 (s, 3 H, CH_3C=CH_2), 3.46 (ddd, J = 10.4, 10.4, 4.3 Hz, 1 H, CH−OH), 4.86 (s, 1 H, C=CHH), 4.90 (s, 1 H, C=CHH). Further verification of the structures of **2** and **3** was based on the PCC oxidation which, in each case, gave isopulegone, whose treatment with methanolic KOH afforded pulegone, identical with an authentic sample purchased from Fluka.

Typical Procedure for the Prins-Type Cyclization (Procedure II). To the in situ generated catalyst **B** (5 mol %) was added H_2O (0.3 mL) followed by a solution of citronellal **1a** (200 mg, 1.3 mmol) in DME (1 mL). The resulting mixture was stirred at room temperature for 48 h and then diluted with ether and worked up. The crude product, which was a 1:4 mixture of **4a** and **5a**, as determined by ^1H NMR, was chromatographed on a column of silica gel (20 g) using a petroleum ether−ether mixture (2:1) to furnish the *cis*-diol **5a** (163 mg, 73%): mp 78−81 °C (lit.[15,17,56,57] mp 73−74 °C or 81−82 °C); IR ν(OH) 3480 and 3610 cm^{-1}; ^1H NMR δ 0.89 (d, J = 6.2 Hz, 3 H, CH_3CH), 1.24 (3 H, pro-*S**-CH_3), 1.37 (s, 3 H, pro-*R**-CH_3), 1.60−1.90 (m, 6 H), 2.95−3.40 (br s, 2 H), 4.42 (br d, J = 2.5 Hz, 1 H, CHOH); ^{13}C NMR δ 20.24 (t), 22.18 (q), 25.56 (d), 28.76 (q), 28.88 (q), 34.83 (t), 42.46 (t), 48.23 (d), 67.98 (d), 73.20 (s); HRMS (EI) m/z 154.135 82 (calcd for $C_{10}H_{18}O$, 154.135 77; $M^{\bullet+} - H_2O$). Continued elution afforded a more polar fraction, identified as the *trans*-diol **4a** (20 mg; 9%): mp 59−60 °C (petroleum ether) (lit.[15,56,57] mp 60−61 °C or 77−78 °C); IR ν(OH) 3480, 3600 cm^{-1}; ^1H NMR δ 0.92 (d, J = 6.5 Hz, 3 H, CH_3CH), 1.23 (s, 6 H, CMe_2), 1.25−2.05 (m, 8 H), 3.72 (dt, J = 10.5 and 4.3 Hz, 1 H, CHOH), 3.88 (br s, 2 H, 2 × OH); ^{13}C NMR δ 22.03 (q), 23.75 (q), 27.15 (t), 30.13 (q), 31.41 (d), 34.59 (t), 44.65 (t), 53.46 (d), 72.95 (d), 75.12 (s).

***(E)*-[8,8,8-$^2H_3$]-3,7-dimethyl-6-octen-1-al (1b).** To a solution of oxalyl chloride (351 mg, 2.77 mmol) in CH_2Cl_2 (19 mL) was added dropwise a solution of DMSO (433 mg, 5.54 mmol) in CH_2Cl_2 (1.6 mL) at −78 °C, and the resulting solution was stirred at −78 °C for 5 min. A solution of the alcohol **42** (410 mg, 2.57 mmol) in CH_2Cl_2 (1.6 mL) was then added at the same temperature. After 15 min, Et_3N (1.8 mL, 13 mmol) was added and the mixture was allowed to warm to room temperature, stirred for 30 min, and then poured into 1 M HCl. The product was extracted with CH_2Cl_2, the organic layer was dried with $MgSO_4$, and the solvent was evaporated. The residue was flash-chromatographed on silica gel (10 g) with a petroleum ether−ether mixture (9:1) to afford **1b** (395 mg; 98%) as a colorless oil: IR ν(C=O) 1725, ν(CH) 2725 cm^{-1}; ^1H NMR δ 0.97 (d, J = 6.6 Hz, 3 H, CHCH_3), 1.10−1.45 (m, 3 H), 1.60 (s, 3 H, CH_3), 1.85−2.52 (m, 4 H), 5.09 (dt, J = 7.1, 1.3 Hz, 1 H, CH=C), 9.75 (t, J = 2.4 Hz, 1 H, CH=O); ^{13}C NMR δ 17.57 (q), 19.82 (q), 25.33 (t), 27.72 (d), 36.89 (t), 50.95 (t), 123.99 (d), 131.69 (s), 203.07 (d); MS ≥97% of d_3.

***(Z)*-[8,8,8-$^2H_3$]-3,7-Dimethyl-6-octen-1-al (1c).** Obtained from **48** on Swern oxidation (in the same way as **1b**) as a colorless oil (92%): IR ν(C=O) 1725; ^1H NMR δ 0.95 (d, J = 6.6 Hz, 3 H, CHCH_3), 1.1−1.45 (m, 3 H), 1.67 (d, J = 1.3 Hz, 3 H, CH_3C=C), 1.83−2.48 (m, 4 H), 5.07 (dt, J = 7.1 and 1.3 Hz, 1 H, C=CH), 9.74 (t, J = 2.2 Hz, 1 H, CH=O); ^{13}C NMR δ 19.84 (q), 25.36 (t), 25.62 (q), 27.74 (d), 36.92 (t), 50.98 (t), 124.02 (d), 131.70 (s), 203.07 (d); MS ≥97% of d_3.

[9,9,9-$^2H_3$]-(1*S,3*S**,4*S**,8*S**)-*p*-Menthane-3,8-diol (4b).** Obtained from citronellal-d_3 (**1b**) as the minor product in the same manner as its nonlabeled counterpart **4a** using procedure II (16%): ^1H NMR δ 0.92 (d, J = 6.6 Hz, 3 H, CHCH_3), 1.21 (s, 3 H, CH_3), 1.23−2.00 (m, 8 H), 3.71 (dt, J = 10.4, 4.2 Hz, 1 H, CHOH), 4.26 (br s, 2 H, 2 × OH); ^{13}C NMR δ 21.94 (q), 26.99 (t), 29.85 (q), 31.31 (d), 34.49 (t), 44.50 (t), 53.24 (d), 72.83 (d), 74.86 (s).

[9,9,9-$^2H_3$]-(1*S,3*R**,4*S**,8*S**)-*p*-Menthane-3,8-diol (5b).** Obtained from citronellal-d_3 (**1b**) as the major product in the same manner as its nonlabeled counterpart **5a** using procedure II (72%): ^1H NMR δ 0.89 (d, J = 6.0 Hz, 3 H, CHCH_3), 0.90−1.20 (m, 3 H), 1.35 (s, 3 H, CH_3), 1.59−1.94 (m, 5 H), 2.59−3.30 (m, 2 H, 2 × OH), 4.39 (d, J = 2.2 Hz, 1 H, CHOH); ^{13}C NMR δ 20.21 (t), 22.17 (q), 25.57 (d), 28.79 (q), 34.81 (t), 42.47 (t), 48.21 (d), 68.03 (d), 73.10 (s); MS m/z (%) 157 ($M^{\bullet+} - H_2O$; 8), 142 (6), 124 (3), 111 (7), 96 (61), 81 (100), 72 (8), 68 (22), 62 (56), 54 (25).

(56) **4a** and **5a**: (a) Nishimura, H.; Kaku, K.; Nakamura, T.; Fukuzawa, Y.; Mizutani, J. *Agric. Biol. Chem.* **1982**, *46*, 319. (b) Nishimura, H.; Noma, Y.; Mizutani, J. *Agric. Biol. Chem.* **1982**, *46*, 2601. (c) Asakawa, Matsuda, R.; Tori, M.; Hashimoto, T. *Phytochemistry* **1988**, *27*, 386. (d) Takahashi, H.; Noma, Y., Toyota, M.; Ashakawa, Y. *Phytochemistry* **1994**, *35*, 1465. **4a**: (e) Stein, D.; Sam, R.; Nouguier, R.; Crich, D.; Bertrand, M. P. *J. Org. Chem.* **1997**, *62*, 275.

(57) The configurational assignment for **4a** and **5a** is based on the coupling pattern of the CHOH in the ^1H NMR. Thus, **5a**, with an axial OH, shows the proton in question as a broad doublet (J = 2.5 Hz), whereas the equatorial epimer **4a** exhibits a dt with J = 10.5 and 4.3 Hz.

(*E*)-8-(Dimethylphenylsilyl)oct-6-en-1-al (9). Obtained from **18** (in the same manner as **10** was prepared from **24**) as a colorless oil (153 mg, 59%): IR ν(CH) 2725, ν(CO) 1725 cm^{-1}; ^{1}H NMR δ 0.26 (s, 6 H, Si(CH$_3$)$_2$), 1.23−1.43 (m, 2 H), 1.49−1.73 (m, 2 H), 1.65 (d, J = 7.6 Hz, 2 H, CH=CHCH_2Si), 1.90−2.05 (m, 2 H), 2.37 (dt, J = 7.5 and 1.80 Hz, 2 H, CH_2CH=O), 5.14−5.46 (m, 2 H, CH=CH), 7.28−7.56 (m, 5 H, aryl-H), 9.73 (t, J = 1.7 Hz, 1 H, CH=O); ^{13}C NMR δ −3.41 (2 × q), 21.42 (t), 21.60 (t), 29.28 (t), 32.33 (t), 43.70 (t), 126.05 (d), 127.66 (d), 128.83 (d), 128.87 (d), 133.58 (d), 138.85 (s), 202.69 (d).

(*Z*)-8-(Dimethylphenylsilyl)oct-6-en-1-al (10). Chromium trioxide (448 mg, 4.5 mmol) was added in three equal portions to pyridine (0.73 mL, 9 mmol) in dry CH_2Cl_2 (7 mL). After the solution was stirred at room temperature for 15 min, a solution of **24** (262 mg, 1.0 mmol) in dry CH_2Cl_2 (2 mL) was added. The reaction mixture was then stirred for 3 h and quenched by pouring into wet ether. The ethereal layer was successively washed with 10% NaOH (2 × 70 mL), a saturated aqueous solution of $CuSO_4$ (4 × 15 mL), water (10 mL), and brine (2 × 15 mL) and dried with $MgSO_4$. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel using a petroleum ether−ether mixture (4:1) as eluent to furnish **10** as a colorless oil (163 mg, 63%): IR ν(CO) 1725 cm^{-1}; ^{1}H NMR δ 0.28 (s, 6 H, Si(CH$_3$)$_2$), 1.06−1.65 (m, 4 H), 1.70 (d, J = 8.5 Hz, 2 H, CH=CHCH_2Si), 1.92 (m, 2 H), 2.37 (dt, J = 7.2, 1.8 Hz, 2 H, CH_2CHO), 5.14−5.53 (m, 2 H, CH=CH), 7.28−7.59 (m, 5 H, aryl-H), 9.72 (t, J = 1.7 Hz, 1 H, CH=O); ^{13}C NMR δ −3.34 (2 × q), 17.61 (t), 21.72 (t), 26.67 (t), 29.06 (t), 43.73 (t), 125.20 (d), 127.44 (d), 127.66 (d), 128.91 (d), 133.54 (d), 138.76 (s), 202.70 (d).

(1*S,2*R**)-2-Vinylcyclohexanol (11):**[58] IR ν(OH) 3600, 3680 cm^{-1}; ^{1}H NMR δ 1.06−1.94 (m, 8 H), 1.94−2.10 (m, 1 H, C*H*CH=CH$_2$), 3.23 (dt, J = 4.0, 10.0 Hz, 1 H, CH$_2$C*H*OH), 5.04−5.21 (m, 2 H, CH=CH_2), 5.66 (ddd, J = 8.0, 10.2, and 17.3 Hz, 1 H, C*H*=CH$_2$); ^{13}C NMR δ 24.75 (t), 25.12 (t), 31.08 (t), 33.81 (t), 51.20 (d), 72.76 (d), 116.66 (t), 140.79 (d).

(1*R,2*R**)-2-Vinylcyclohexanol (12):**[58a] IR ν(OH) 3590, 3660 cm^{-1}; ^{1}H NMR δ 1.05−1.78 (m, 8 H), 2.09−2.30 (m, 1 H, C*H*CH=CH$_2$), 3.79−3.89 (m, 1 H, CH$_2$C*H*OH), 5.04−5.19 (m, 2 H, CH=CH_2), 5.92 (ddd, J = 6.6, 10.7, and 17.3 Hz, 1 H, C*H*=CH$_2$); ^{13}C NMR δ 20.83 (t), 24.20 (t), 25.51 (t), 32.10 (t), 45.23 (d), 69.29 (d), 115.96 (t), 140.80 (d).

Ethyl (*E*)-8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octenoate (14). Aldehyde **13** (2.2 g, 11.0 mmol) was added dropwise over a period of 15 min to a refluxing solution of (carbethoxymethylene)triphenylphosphorane (3.83 g, 11.0 mmol) in benzene (10 mL). TLC analysis with a hexane−AcOEt mixture (4:1) indicated that the reaction was complete after 3 h. The solvent was evaporated, and the residue was dissolved in hexane and filtered through silica gel to remove triphenylphosphine oxide. Evaporation of the solvent furnished the unsaturated ester **14** (96:4) (2.64 g, 89%) as a colorless oil, whose spectral data correspond to those described in the literature:[24] IR ν(C=O) 1710, ν(C=C) 1657 cm^{-1}; ^{1}H NMR δ 1.28 (t, J = 7.1 Hz, 3 H, CH$_3$), 1.35−1.55 (m, 12 H), 2.13−2.59 (m, 2 H, CH_2CH=C), 3.31−3.94 (m, 4 H, 2 × CH$_2$O), 4.18 (q, J = 7.1 Hz, 2 H, OCH_2CH$_3$), 4.57 (m, 1 H, OCHO), 5.81 (d, J = 15.7 Hz, 1 H, CH=C*H*CO$_2$Me), 6.19 (dt, J = 15.7, 6.9 Hz, 1 H, C*H*=CHCO$_2$Me); ^{13}C NMR δ 14.20 (q), 19.64 (t), 25.43 (t), 25.74 (t), 27.79 (t), 29.43 (t), 30.70 (t), 30.03 (t), 60.04 (t), 62.31 (t), 67.31 (t), 98.83 (d), 121.33 (d), 149.07 (d), 166.65 (s).

(*E*)-8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octen-1-ol (15). Obtained from **14** on diisobutylaluminum hydride reduction (in the same way as **21** was prepared from **20**) as a colorless oil (103 mg, 90%), whose spectral data correspond to those described in the literature:[24a,b,25] IR ν(OH) 3605, 3440 cm^{-1}; ^{1}H NMR δ 1.27−1.94 (m, 13 H), 1.97−2.16 (m, 2 H, CH_2CH=C), 3.30−3.95 (m, 4 H, 2 × CH$_2$O), 4.07 (d, J = 4.4 Hz, 2 H, CH_2OH), 4.57 (m, 1 H, OCHO), 5.47−5.78 (m, 2 H, CH=CH); ^{13}C NMR δ 19.61 (t), 25.42 (t), 25.69 (t), 28.87 (t), 29.49 (t), 30.69 (t), 32.04 (t), 62.29 (t), 63.62 (t), 67.48 (t), 98.80 (d), 129.03 (d), 133.01 (d).

(*E*)-8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octenyl Acetate (16). Obtained from **15** on acetylation (in the same way as **22** was prepared from **21**) as a colorless oil (2.02 g, 93%): IR ν(C=O) 1730 cm^{-1}; ^{1}H NMR δ 1.23−1.86 (m, 10 H), 1.97−2.17 (m, 2 H, CH_2CH=C), 2.06 (s, 3 H, COCH$_3$), 3.31−3.94 (m, 4 H, 2 × CH$_2$O), 4.50 (d, J = 6.5 Hz, 2 H, CH_2OAc), 4.57 (m, 1 H, OCHO), 5.47−5.66 (m, 1 H, C*H*=CH), 5.68−5.86 (m, 1 H, CH=C*H*); ^{13}C NMR δ 19.60 (t), 20.90 (q), 25.40 (t), 25.67 (t), 28.61 (t), 29.46 (t), 30.68 (t), 32.06 (t), 62.24 (t), 65.15 (t), 67.39 (t), 98.77 (d), 123.78 (d), 136.29 (d), 170.71 (s).

(*E*)-7-[(Tetrahydro-2′*H*-pyran-2-yl)oxy]-1-[(dimethylphenylsilyl)methyl]hept-1-ene (17). Obtained from **16** (in the same way as **23** was prepared from **22**) as a colorless oil **17** (0.90 g, 67%): ^{1}H NMR δ 0.25 (s, 6 H, Si(CH$_3$)$_2$), 1.15−1.84 (m, 10 H), 1.65 (d, J = 7.5 Hz, 2 H, CH=CHCH_2Si), 1.96 (m, 2 H, CH_2CH=C), 3.27−3.95 (m, 4 H, 2 × CH$_2$O), 4.57 (m, 1 H, OCHO), 5.14−5.46 (m, 2 H, CH=CH), 7.27−7.60 (m, 5 H, aryl-H); ^{13}C NMR δ −3.43 (2 × q), 19.64 (t), 21.55 (t), 25.49 (t), 25.66 (t), 29.60 (t), 29.72 (t), 30.75 (t), 32.64 (t), 62.23 (t), 67.59 (t), 98.77 (d), 125.38 (d), 127.63 (d), 128.82 (d), 129.60 (d), 133.58 (d), 138.96 (s).

(*E*)-7-[(Dimethylphenylsilyl)methyl]-1-hydroxyhept-6-ene (18). Obtained from **17** on deprotection (in the same way as **24** was prepared from **23**) as a colorless oil (89%): IR ν(OH) 3615 cm^{-1}; ^{1}H NMR δ 0.25 (s, 6 H, Si(CH$_3$)$_2$), 1.20−1.61 (m, 7 H), 1.65 (d, J = 7.2 Hz, 2 H, CH=CHCH_2Si), 1.85−2.05 (m, 2 H, CH_2CH=C), 3.61 (t, J = 6.6 Hz, 2 H, CH_2OH), 5.15−5.47 (m, 2 H, CH=CH), 7.29−7.56 (m, 5 H, aryl-H); ^{13}C NMR δ −3.43 (2 × q), 21.56 (t), 25.10 (t), 29.63 (t), 32.62 (2 × t), 62.97 (t), 125.53 (d), 127.64 (d), 128.84 (d), 129.48 (d), 133.59 (d), 138.97 (s).

Methyl 8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octynoate (19). To a mixture of zinc dust (1.30 g, 2 equiv) and tetrabromomethane (6.64 g, 2 equiv) in CH_2Cl_2 (28 mL) was added triphenylphosphine (5.24 g, 2 equiv.) portionwise. After 24 h at 23 °C, a solution of 6-(tetrahydro-2′-pyranyloxy)hexanal (**13**)[5b] (2.0 g, 10 mmol, 1 equiv) in CH_2Cl_2 (10 mL) was slowly added. The mixture was stirred for 90 min, poured into hexane (540 mL), and filtered, and the solvent was evaporated under reduced pressure. The residue was diluted with hexane (100 mL), and triphenylphosphine oxide was removed by filtration. Upon removal of solvent, essentially pure 1,1-dibromoolefin (3.28 g, 92%) was obtained as a colorless oil: ^{1}H NMR δ 2.10 (q, J = 7.1 Hz, 2 H, CH$_2$CH=C), 3.27−3.93 (m, 4 H, 2 × CH$_2$O), 4.56 (m, 1 H, OCHO), 6.37 (t, J = 7.2 Hz, 1 H, CH$_2$C*H*=CBr$_2$); ^{13}C NMR δ 19.67 (t), 25.48 (t), 25.71 (t), 27.62 (t), 29.44 (t), 30.75 (t), 32.91 (t), 62.32 (t), 67.31 (t), 88.64 (s), 98.85 (d), 138.64 (d); HRMS m/z 354.9731 (calcd for $C_{12}H_{19}O_2Br_2$, 354.9731; M$^{\bullet+}$ − H). To a solution of the latter dibromoolefin (847 mg, 2.38 mmol), obtained from the above reaction, in THF (30 mL), was added dropwise *n*-BuLi (3.14 mL, 5.02 mmol, 1.6 M solution in hexane) at −78 °C under nitrogen. After 20 min, methyl chloroformate (0.92 mL, 11.9 mmol) was added dropwise. The mixture was stirred at −78 °C for 10 min, allowed to warm to room temperature for 45 min, and then poured into ether and brine. The organic layer was washed with an aqueous solution of $NaHCO_3$ and with brine and dried over $MgSO_4$, and the solvent was evaporated. The crude product was purified by flash chromatography on silica gel using a hexane−AcOEt mixture (30:1) as eluent to furnish **19** (0.49 g, 81%) as an oil, whose spectral data correspond to those described in the literature:[31] IR ν 2235, 1710 cm^{-1}; ^{1}H NMR δ 1.05−1.90 (m, 12 H), 2.31 (t, J = 6.9 Hz, 2 H, CH$_2$C≡C), 3.25−3.95 (m, 4 H, 2 × CH$_2$O), 3.71 (s, 3 H, OCH$_3$), 4.53 (m, 1 H, OCHO); ^{13}C NMR δ 18.54 (t), 19.59 (t), 25.42 (t), 25.49 (t), 27.30 (t), 29.08 (t), 30.68 (t), 52.41 (q), 62.26 (t), 67.12 (t), 72.89 (s), 89.55 (s), 98.81 (d), 154.14 (s).

Methyl (*Z*)-8-[(tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octenoate (20). A mixture of acetylene **19** (0.52 g, 2.04 mmol), quinoline (0.75 mL, 6.33 mmol), and Lindlar catalyst (0.37 g) in hexane (57 mL) was stirred under 1 atm of H_2 (g) for 4.5 h. After removal of the solids by filtration through Celite, the

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solution was washed with 1 M HCl, water, an aqueous solution of $NaHCO_3$, and brine and dried over $MgSO_4$. Upon removal of the solvent, pure **20** (517 mg, 99%) was obtained as a colorless oil: IR ν 1718, 1645 cm^{-1}; ^1H NMR δ 1.10−1.95 (m, 12 H), 2.63 (m, 2 H, C*H*$_2$CH=C), 3.25−3.92 (m, 4 H, 2 × CH_2O), 3.66 (s, 3 H, OCH_3), 4.53 (m, 1 H, OCHO), 5.73 (d, J = 11.6 Hz, 1 H, CH=C*H*CO_2Me), 6.19 (dt, J = 11.3, 7.6 Hz, 1 H, C*H*=CHCO_2Me); ^{13}C NMR δ 19.60 (t), 25.46 (t), 25.90 (t), 28.79 (t), 28.87 (t), 29.48 (t), 30.71 (t), 50.86 (q), 62.22 (t), 67.37 (t), 98.75 (d), 119.23 (d), 150.62 (d), 166.74 (s).

(*Z*)-8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octen-1-ol (21). To a solution of **20** (128 mg, 0.5 mmol) in toluene (10 mL) at −20 °C was added diisobutylaluminum hydride (1.0 mL, 1.0 M solution in toluene). After 25 min, water (2.5 mL) was added dropwise and the resulting solution was allowed to warm to room temperature over 2 h. The product was extracted with ether, the combined organic layers were dried over $MgSO_4$, and the solvent was evaporated to furnish the required product **21** (96 mg, 84%): IR ν(OH) 3618, 3680 cm^{-1}; ^1H NMR δ 1.21−1.93 (m, 13 H), 1.93−2.14 (m, 2 H, C*H*$_2$CH=C), 3.28−3.91 (m, 4 H, 2 × CH_2O), 4.15 (s, 2 H, C*H*$_2$OH), 4.54 (m, 1 H, OCHO), 5.39−5.67 (m, 2 H, CH=CH); ^{13}C NMR δ 19.60 (t), 25.40 (t), 25.66 (t), 27.14 (t), 29.21 (t), 29.41 (t), 30.67 (t), 58.39 (t), 62.29 (t), 67.47 (t), 98.82 (d), 128.61 (d), 132.63 (d).

(*Z*)-8-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-2-octenyl Acetate (22). To a solution of alcohol **21** (1.83 g, 8.06 mmol) in dry THF (17 mL) at room temperature was added pyridine (0.97 mL, 12 mmol). Acetic anhydride (1.13 mL, 12 mmol) was then added, and the resulting reaction mixture was stirred overnight. Evaporation of the solvent afforded a crude residue which was diluted with ether (150 mL) and washed with saturated aqueous solution of $CuSO_4$ (2 × 15 mL), water (10 mL), a saturated aqueous solution of $NaHCO_3$ (2 × 15 mL), and brine (10 mL). The ethereal layer was dried with $MgSO_4$, filtered, and evaporated. The residue was chromatographed on a column of silica gel (50 g) with a petroleum ether−ether mixture (9:1) to furnish **22** (1.98 g, 91%): IR ν(C=O) 1730 cm^{-1}; ^1H NMR δ 1.89−1.26 (m, 12 H), 2.08 (m, 2 H, C*H*$_2$CH=CH), 2.06 (s, 3 H, CO_2CH_3), 3.27−3.94 (m, 4 H, 2 × CH_2O), 4.57 (m, 1 H, OCHO), 4.61 (d, J = 6.6 Hz, 2 H, =CHC*H*$_2$OH), 5.44−5.92 (m, 2 H, CH=CH); ^{13}C NMR δ 19.62 (t), 20.92 (q), 25.44 (t), 25.79 (t), 27.41 (t), 29.20 (t), 29.52 (t), 30.71 (t), 60.30 (t), 62.26 (t), 67.42 (t), 98.79 (d), 123.35 (d), 135.18 (d), 170.90 (s).

(*Z*)-7-[(Tetrahydro-2′*H*-pyran-2′-yl)oxy]-1-[(dimethylphenylsilyl)methyl]hept-1-ene (23). Phenyldimethylchlorosilane (1.29 mL, 7.8 mmol) was added to a suspension of finely cut lithium wire (275 mg) in dry THF (15 mL). After being stirred for 90 min at room temperature, the solution turned dark red. Continued vigorous stirring for 3 h then produced a brownish solution which was transferred with the aid of a cannula to a suspension of CuCN (0.49 g, 5.5 mmol) in dry THF (7 mL) at 0 °C. After 90 min, the reaction mixture was cooled to −60 °C and a solution of acetate **22** (1.05 g, 3.9 mmol) in dry THF (7 mL) was added. The resulting mixture was stirred at −60 °C for 12 h, poured into a 1:1 mixture of saturated aqueous NH_4Cl/saturated aqueous Na_2CO_3 (250 mL), and extracted with ether. The combined ethereal layers were dried, filtered, and evaporated. The residue was chromatographed on silica gel using a hexanes−ether mixture (30:1 to 4:1) to furnish **23** (1.01 g, 75%) as a colorless oil: ^1H NMR δ 0.27 (s, 6 H, Si$(CH_3)_2$), 1.0−1.68 (m, 10 H), 1.72 (d, J = 7.9 Hz, 2 H, CH=CHC*H*$_2$Si), 1.90−1.99 (m, 2 H), 3.25−3.96 (m, 4 H, 2 × CH_2O), 4.57 (m, 1 H, OCHO), 5.17−5.47 (m, 2 H, CH=CH), 7.28−7.57 (m, 5 H, aryl-H); ^{13}C NMR δ −3.31 (2 × q), 17.50 (t), 19.65 (t), 25.49 (t), 26.00 (t), 27.01 (t), 29.50 (t), 29.65 (t), 30.75 (t), 62.25 (t), 67.58 (t), 98.79 (d), 124.62 (d), 127.66 (d), 128.25 (d), 128.89 (d), 133.53 (d), 138.92 (s).

(*Z*)-7-[(Dimethylphenylsilyl)methyl]-1-hydroxyhept-6-ene (24). A solution of **23** (346 mg, 1.0 mmol) in MeOH (15 mL) was stirred in the presence of *p*-toluenesulfonic acid (30 mg) at room temperature. After 7 h, the mixture was poured into a saturated aqueous solution of $NaHCO_3$, extracted with ether, and dried over $MgSO_4$. The solvent was evaporated under reduced pressure, and the residue was purified on silica gel (10 g) by eluting with a hexanes−ether mixture (4:1) to afford **24** (249 mg, 95%) as a colorless oil: IR ν(OH) 3620 cm^{-1}; ^1H NMR δ 0.27 (s, 6 H, Si$(CH_3)_2$), 1.16−1.64 (m, 7 H), 1.70 (d, J = 7.9 Hz, 2 H, CH=CHC*H*$_2$Si), 1.93 (m, 2 H, C*H*$_2$CH=C), 3.61 (t, J = 6.4 Hz, 2 H, C*H*$_2$OH), 5.16−5.48 (m, 2 H, CH=CH), 7.28−7.61 (m, 5 H, aryl-H); ^{13}C NMR δ −3.32 (2 × q), 17.52 (t), 25.44 (t), 26.98 (t), 29.41 (t), 32.65 (t), 62.93 (t), 124.75 (d), 127.66 (d), 128.09 (d), 128.90 (d), 133.55 (d), 138.88 (s).

5-Methyl-5-hexen-1-al (25). To a stirred solution of ethyl 4-isopropenylbutyrate[59] (0.48 g, 3 mmol) in dichloromethane (30 mL) at −78 °C was added diisobutylaluminum hydride (6 mmol, 1 M solution in CH_2Cl_2) over a period of 20 min under nitrogen atmosphere. After 10 min, the reaction mixture was quenched with saturated aqueous solution of ammonium chloride and allowed to warm to room temperature over 0.5 h. The product was extracted with ether and dried with $MgSO_4$. After filtration, the solvent was removed under reduced pressure and the residual oil was flash chromatographed on silica gel (10 g) eluting with hexanes−ether mixture (16:1) to furnish **25** (218 mg, 65%) as a colorless oil:[35] ^1H NMR δ 1.64 (s, 3 H, CH_3), 1.70 (m, 2 H) 1.98 (t, J = 7.4 Hz, 2 H), 2.36 (dt, J = 7.3 and 1.7 Hz, 2 H), 4.62 (s, 1 H, C=CH*H*), 4.68 (s, 1 H, C=C*H*H), 9.71 (t, J = 1.6 Hz, 1 H, CHO); ^{13}C NMR δ 19.83 (t), 22.10 (q), 36.93 (t), 43.21 (t), 110.82 (t), 144.59 (s), 202.41 (d).

3-Methylenecyclohexan-1-ol (26):[35] ^1H NMR δ 3.75 (m, 1 H, C*H*OH), 4.70 (s, 1 H, C=C*H*H), 4.74 (s, 1 H, C=CH*H*); identical with an authentic sample prepared by a literature procedure.[35]

3-Methylcyclohex-3-en-1-ol (27):[60] ^1H NMR δ 1.58 (s, 3 H, CH_3), 3.86 (br s, 1 H, C*H*OH), 5.29 (m, 1 H, CH=C); identical with an authentic sample prepared by a literature procedure.[60]

3-(2′-Methylenecyclohexyl)propanal (28). Obtained on diisobutylaluminum hydride reduction of ethyl 3-(2′-methylenecyclohexyl)propionate[61] (in the same way as **25** was prepared from ethyl 4-isopropenylbutyrate) as a colorless oil (120 mg, 26%):[36] ^1H NMR δ 1.15−1.72 (m, 7 H), 1.77−2.06 (m, 3 H), 2.07−2.19 (m, 1 H), 2.44−2.47 (m, 2 H), 4.57 (s, 1 H, C=C*H*H), 4.69 (s, 1 H, C=CH*H*), 9.75 (t, J = 1.5 Hz, 1 H, CHO); ^{13}C NMR δ 26.90 (t), 28.59 (t), 31.58 (t), 33.69 (t), 34.22 (t), 42.16 (t), 42.57 (d), 106.55 (t), 151.60 (s), 202.75 (d).

(2*R,5*S**)-1,2,3,4,4a,5,6,7-octahydronaphthalen-2-ol (29)[36,62] and 1,2,3,4,5,6,7,8-octahydronaphthalen-2-ol (30).**[36,63] **Method A.** Cyclization of **28** was carried according to procedure I: To a DME solution of $PhCH_2(Et)_3N^+[Mo(CO)_4ClBr_2]^-$ (**A**) as catalyst (5 mol %) was added a solution of **28** (152 mg, 1.0 mmol) in DME (1 mL). The mixture was stirred at room temperature for 30 min and worked up. Chromatography on silica gel using a hexanes−ether mixture (6:1 to 4:1) afforded **29**[36,62] (126 mg, 83%): IR (neat) ν(OH) 3350, 1440, 1040, 945 cm^{-1}; ^1H NMR δ 1.16−2.07 (m, 12 H), 2.17−2.29 (m, 2 H), 4.07 (m, 1 H, C*H*OH), 5.52 (m, 1 H, C=CH); ^{13}C NMR δ 21.14 (t), 25.59 (t), 28.71 (t), 30.58 (t), 32.33 (t), 36.93 (d), 42.55 (t), 67.15 (d), 124.02 (d), 136.11 (s). Continued elution gave the more polar isomer **30**[36,63] (26 mg, 17%): ^1H NMR δ 1.10−2.58 (m, 15 H), 3.85−4.0 (m, 1 H); ^{13}C NMR δ 22.89 (t), 23.02 (t), 28.43 (t), 29.80 (t), 39.42 (t), 30.23 (t), 31.26 (t), 67.46 (d), 125.19 (s), 127.50 (s).

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Method B. Cyclization of **28** was carried according to procedure II: Silver(I) trifluorosulfonate (50 mg, 3 equiv) was added to a stirred suspension of $C_6H_5CH_2(C_2H_5)_3N^+$-$[Mo(CO)_5Br]^-\cdot nH_2O$ (30 mg; 1 equiv) in DME (2 mL) at 0 °C under nitrogen. The reaction mixture was allowed to warm to room temperature and stirred for 15 min. To the catalyst thus generated (5 mol %) was added a solution of **28** (198 mg, 1.3 mmol) in DME (1 mL). The resulting mixture was stirred at room temperature for 30 min and then diluted with ether and worked up. The crude product was chromatographed on silica gel using a hexanes−ether mixture (5:1) to furnish **29** (79 mg, 40%) and **30** (95 mg, 48%).

6-(Benzyloxy)-4-methylhexanal (37). A steady stream of ozone in oxygen generated with a Wallace and Tiernan ozonizer was bubbled through a solution of 1-(benzyloxy)-3,7-dimethyloct-6-ene (12.3 g, 50 mmol) and pyridine (4.3 mL, 50 mmol) in dry CH_2Cl_2 (120 mL) for 4.5 h at −78 °C. Dimethyl sulfide (8.6 mL) was added, and the solution was allowed to warm to room temperature. After 5 h, the volatile materials were removed under reduced pressure and the residue was diluted with water and extracted with hexane. The combined organic layers were washed with 5% HCl and brine, dried with $MgSO_4$, and evaporated. The crude product (11 g) was purified by flash chromatography on a column of silica gel using petroleum ether−ether mixture (9:1) as eluent to furnish **37** (6.65 g, 61%), whose spectral data correspond to those described in the literature:[38] IR (neat) ν(CH) 2725, ν(C=O) 1725 cm^{-1}; ^1H NMR δ 0.93 (d, J = 6.0 Hz, 3 H, CHCH_3), 1.37−1.88 (m, 5 H), 2.34−2.56 (m, 2 H, CH_2CHO), 3.54 (t, J = 6.4 Hz, 2 H, CH_2CH_2O), 4.52 (s, 2 H, OC$H_2C_6H_5$), 7.36 (s, 5 H, aryl-H), 9.78 (t, J = 1.7 Hz, 1 H, CHO); ^{13}C NMR δ 19.22 (q), 28.78 (t), 29.44 (d), 36.37 (t), 41.52 (t), 68.18 (t), 72.89 (t), 127.46 (d), 127.54 (d), 128.28 (d), 138.45 (s), 202.65 (d).

Ethyl (*E*)-2,6-Dimethyl-8-(benzyloxy)-2-octenoate (38). Aldehyde **37** (1.16 g, 5.26 mmol) was added dropwise over a period of 15 min to a refluxing solution containing ethyl 2-(triphenylphosphoranylidene)propionate (2.4 g, 6.64 mmol) in dichloromethane (5 mL). After 4 h, the reaction was found to be complete by TLC analysis with hexanes−ethyl acetate mixture (5:1) as the developing solvent. The solvent was evaporated, and the residue was dissolved in petroleum ether and filtered through silica gel (10 g) to remove starting phosphorane and triphenylphosphine oxide. Removal of the solvent under reduced pressure gave unsaturated ester **38** as a 98:2 *E*/*Z* mixture (1.48 g, 93%):[40] IR ν(C=O) 1700, ν(C=C) 1645, and ν(C−O) 1270 cm^{-1}; ^1H NMR δ 0.69 (d, J = 6.3 Hz, 3 H, CHCH_3), 1.15−1.58 (m, 5 H), 1.07 (t, J = 7.1 Hz, 3 H, $CO_2CH_2CH_3$), 1.61 (s, 3 H, CH_3), 1.95 (m, 2 H, CH_2CH=C), 3.28 (t, J = 6.5 Hz, 2 H, CH_2OBn), 3.96 (q, J = 7.2 Hz, 2 H, OCH_2CH$_3$), 4.28 (s, 2 H, OC$H_2C_6H_5$), 6.52 (t, J = 7.6 Hz, 1 H, vinyl-H), 7.11 (s, 5 H, aryl-H); ^{13}C NMR δ 12.27 (q), 14.26 (q), 19.37 (q), 26.16 (t), 29.67 (d), 35.72 (t), 36.53 (t), 60.34 (t), 68.42 (t), 72.92 (t), 127.47 (d), 127.58 (d), 128.40 (d), 138.54 (s), 141.05 (s), 142.29 (d), 168.24 (s).

(*E*)-[8,8-$^2H_2$]-1-(Benzyloxy)-3,7-dimethyl-6-octen-8-ol (39). To a suspension of lithium aluminum deuteride (90 mg; 2.14 mmol; ≥96% ^2H-enrichment) in Et_2O (30 mL) at 0 °C was added dropwise over a period of 15 min a solution of ethyl (*E*)-2,6-dimethyl-8-(benzyloxy)octenoate[64] (**38**) (650 mg; 2.14 mmol) in Et_2O (5 mL), and the mixture was stirred at room temperature for 10 min. Solid, anhydrous Na_2SO_4 was added and the excess of the reagent was decomposed by a slow addition of water. The solid was filtered off, the filtrate was washed with brine and dried with $MgSO_4$, and the solvent was evaporated. The residue was purified by flash chromatography on silica gel (14 g) using a hexane−AcOEt mixture (9:1) as eluent to afford **39** (499 mg, 89%):[41] IR ν(OH) 3610 cm^{-1}; ^1H NMR δ 0.73 (d, J = 6.3 Hz, 3 H, CH_3), 0.90−1.68 (m, 6 H), 1.48 (s, 3 H, CH_3), 1.87 (m, 2 H, CH_2CH=C), 3.34 (t, J = 6.7 Hz, 2 H, $CH_2CH_2OCH_2$), 4.33 (s, 2 H, OC$H_2C_6H_5$), 5.21 (t, J = 7.2 Hz, 1 H, C=CH), 7.16 (s, 5 H, arom); ^{13}C NMR δ 13.5 (q), 19.4 (q), 24.9 (t), 29.4 (d), 36.6 (t), 36.7 (t), 68.5 (t), 72.8 (t), 126.5 (d), 127.4 (d), 127.5 (d), 128.3 (d), 134.4 (s), 138.5 (s); MS ≥98% of d_2.

(*E*)-[8,8-$^2H_2$]-1-(Benzyloxy)-3,7-dimethyl-6-octen-8-yl Chloride (40). To a solution of *N*-chlorosuccinimide (294 mg; 2.2 mmol) in dry CH_2Cl_2 (10 mL) was added dropwise dimethyl sulfide (0.176 mL; 2.4 mmol) at 0 °C under nitrogen. The reaction mixture was cooled to −20 °C, and a solution of the alcohol **39** (528 mg; 2 mmol) in CH_2Cl_2 (1 mL) was added gradually over a period of 10 min. The resulting solution was allowed to warm to 0 °C, stirred for 5 h at that temperature, and poured into an ice-cold brine (10 mL). The organic layer was separated, and the aqueous phase was extracted with Et_2O (2 × 5 mL). The combined organic layers were washed with two 5 mL portions of cold brine and dried over $MgSO_4$. Upon removal of the solvent, pure allylic chloride **40** (520 mg, 92%)[41,43] was obtained as a yellow oil: ^1H NMR δ 0.89 (d, J = 6.6 Hz, 3 H, CH_3), 1.10−1.71 (m, 5 H), 1.72 (s, 3 H, CH_3), 1.91−2.15 (m, 2 H, CH_2CH=C), 3.44−3.58 (m, 2 H, CH_2OCH$_2$Ph), 4.49 (s, 2 H, OCH_2Ph), 5.50 (m, J = 7.2, 1.3 Hz, 1 H, C=CH), 7.33 (s, 5 H, arom); ^{13}C NMR δ 13.99 (q), 19.44 (q), 25.47 (t), 29.53 (d), 36.37 (t), 36.60 (t), 68.52 (t), 72.90 (t), 127.47 (d), 127.59 (d), 128.31 (d), 131.16 (d), 131.32 (s), 138.59 (s).

(*E*)-[8,8,8-$^2H_3$]-1-(Benzyloxy)-3,7-dimethyl-6-octene (41). To a solution of the allylic chloride **40** (340 mg; 1.2 mmol) in ether (6.2 mL) was added lithium aluminum deuteride (51 mg; ≥96% ^2H-enrichment). After 6 h at reflux a single spot on the TLC plate was observed. Dry Na_2SO_4 was added, followed by slow addition of water to decompose the excess of the reagent. After removal of the solids by filtration, the ethereal solution was washed with brine and dried with $MgSO_4$, and the solvent was evaporated to yield the benzyl ether **41** (290 mg; 97%)[44] as a colorless oil: ^1H NMR δ 0.81 (d, J = 6.3 Hz, 3 H, CH_3), 0.95−1.72 (m, 5 H), 1.52 (s, 3 H, CH_3), 1.91 (m, 2 H, CH_2CH=C), 3.42 (m, J = 6.8, 1.9 Hz, 2 H, CH_2OCH$_2$Ph), 4.42 (s, 2 H, PhCH_2O), 5.02 (br t, J = 7.1 Hz, 1 H, C=CH), 7.25 (s, 5 H, arom); ^{13}C NMR δ 17.55 (q), 19.53 (q), 25.43 (t), 29.53 (d), 36.70 (t), 37.18 (t), 68.70 (t), 72.88 (t), 124.79 (d), 127.43 (d), 127.58 (d), 128.31 (d), 131.01 (s), 138.67 (s); MS ≥98% of d_2.

(*E*)-[8,8,8-$^2H_3$]-3,7-Dimethyl-6-octen-1-ol (42). A solution of the benzyl ether **41** (880 mg; 3.53 mmol) in THF (20 mL) was added slowly to a solution of lithium (2.58 g; 112 mmol; 30% dispersion in oil; containing 1% sodium) in ammonia (70 mL) at −78 °C. After 15 min, the excess of lithium was decomposed by adding 3-hexyne until the blue color was completely dissipated and the resulting yellow solution was then quenched with methanol until colorless. At rt, water was added and the volatiles were carefully removed by rotary evaporation under reduced pressure. The resulting cloudy solution was extracted with ether (4 × 60 mL), and the combined ethereal layers were washed with water and brine and dried with $MgSO_4$. After filtration, the solvent was removed under reduced pressure and the residue was chromatographed on silica gel (45 g) with a petroleum ether−ether mixture (9:1) followed by pure ether to furnish **42** as a colorless oil (0.51 g; 91%):[44] IR ν(OH) 3620 and 3680 cm^{-1}; ^1H NMR δ 0.78 (d, J = 6.6 Hz, 3 H, CH_3CH), 0.94−1.66 (m, 6 H), 1.48 (s, 3 H, CH=CCD$_3$CH_3), 1.76−1.98 (m, 2 H, CH_2CH=C), 3.40−3.67 (m, 2 H, CH_2OH), 4.97 (br t, J = 7.1 Hz, 1 H, CH=C); ^{13}C NMR δ 17.54 (q), 19.46 (q), 25.39 (t), 29.11 (d), 37.16 (t), 39.84 (t), 61.11 (t), 124.66 (d), 131.15 (s).

(*Z*)-1-(Benzyloxy)-3,7-dimethyl-6-octen-8-ol (43). To a stirred solution of ethyltriphenylphosphonium bromide (1.86 g, 5 mmol) in THF (7 mL) was added butyllithium (1.6 M, 3.1 mL) at 0 °C. After 1 h at that temperature the mixture was cooled to −78 °C, 6-(benzyloxy)-4-methylhexanal (**37**)[65] (1.1 g, 5 mmol) was added dropwise, and the mixture was stirred for 5 min at −78 °C. Additional butyllithium (1.6 M, 3.1 mL) was then added, resulting in the formation of the deep red ylide. The mixture was allowed to reach 0 °C, and then paraformaldehyde (0.30 g) was added. Stirring was continued at 0 °C for 1 h and then for 10 h at room temperature followed by

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addition of ice−water and extraction with ether. The ethereal extract was worked up, and the residue was purified on silica gel (15 g), using a petroleum ether−ether mixture (7:1 to 3:1) as eluent to afford the (*Z*)-alcohol **43** (93:7) (590 mg, 45%) as a colorless oil: IR ν(OH) 3450, 3615 cm^{-1}; ^{1}H NMR δ 0.87 (d, J = 6.6 Hz, 3 H, CH_3), 1.02−1.74 (m, 6 H), 1.78 (s, 3 H, CH_3), 1.90−2.25 (m, 2 H, CH_2CH=C), 3.41−3.59 (m, 2 H, CH_2CH_2-OCH_2), 4.10 (m, 2 H, CH_2OH), 4.49 (s, 2 H, OC$H_2C_6H_5$), 5.25 (t, J = 7.6 Hz, 1 H, C=CH), 7.33 (s, 5 H, aryl-H); ^{13}C NMR δ 19.58 (q), 21.26 (q), 24.89 (t), 28.97 (d), 36.30 (t), 37.17 (t), 61.42 (t), 68.32 (t), 72.91 (t), 127.50 (d), 127.66 (d), 128.32 (d), 128.48 (d), 134.30 (s), 138.46 (s).

Methyl (*Z*)-8-(Benzyloxy)-2,6-dimethyl-2-octenoate (44). A mixture of the allylic alcohol **43** (500 mg) and active manganese dioxide[66] (5.75 g) in hexane (80 mL) was stirred at 0 °C for 30 min. Filtration and evaporation of solvent under reduced pressure furnished (*Z*)-1-(benzyloxy)-3,7-dimethyl-6-octen-8-al (487 mg, 98%): IR ν 1095, 1380, 1455, 1670, 2865, 2925, 2955 cm^{-1}; ^{1}H NMR δ 0.92 (d, J = 6.3 Hz, 3 H, CH_3), 1.76 (s, 3 H, CH_3), 2.46−2.66 (m, 2 H, CH_2CH=C), 3.40−3.59 (m, 2 H, $CH_2CH_2OCH_2$), 4.50 (s, 2 H, OC$H_2C_6H_5$), 6.49 (t, J = 8.0 Hz, 1 H, C=CH), 7.33 (s, 5 H, aryl-H); ^{13}C NMR δ 16.39 (q), 19.28 (q), 24.18 (t), 29.45 (d), 36.51 (t), 36.95 (t), 68.22 (t), 72.93 (t), 127.50 (d), 127.58 (d), 128.32 (d), 135.81 (s), 138.46 (s), 149.77 (d), 191.06 (d). The aldehyde thus obtained was stirred with a mixture of sodium cyanide (0.82 g), acetic acid (0.30 g), and manganese dioxide (5.75 g) in dry methanol (45 mL) for 12 h at 20−25 °C. After removal of methanol, the residue was partitioned between ether and water. Evaporation of the ethereal extract afforded the desired crude product. Further purification was carried out by flash chromatography on silica gel (20 g) using a hexanes−ether mixture (9:1) as eluent to yield **44** as a colorless oil (265 mg, 48%): IR ν(CO) 1710 cm^{-1}; ^{1}H NMR δ 0.90 (d, J = 6.3 Hz, 3 H, CH_3), 1.03−1.77 (m, 5 H), 1.89 (d, J = 1.3 Hz, 3 H, CH_3C=CH), 2.35−2.58 (m, 2 H, CH_2CH=C), 3.51 (m, J = 6.9, 1.9 Hz, 2 H, CH_2CH_2-OCH_2), 3.72 (s, 3 H, OCH_3), 4.50 (s, 2 H, OC$H_2C_6H_5$), 5.92 (t, J = 7.4 Hz, 1 H, C=CH), 7.33 (s, 5 H, aryl-H); ^{13}C NMR δ 19.37 (q), 20.66 (q), 27.06 (t), 29.61 (d), 36.58 (t), 36.61 (t), 51.16 (q), 68.55 (t), 72.86 (t), 126.60 (s), 127.43 (d), 127.56 (d), 128.30 (d), 138.61 (s), 143.67 (d), 168.45 (s).

(*Z*)-[8,8-$^2H_2$]-1-(Benzyloxy)-3,7-dimethyl-6-octen-8-ol (45). Obtained from **44** on $LiAlD_4$ reduction (in the same way as **39** was prepared from **38**) as a colorless oil (86%): IR ν(OH) 3615 cm^{-1}; ^{1}H NMR δ 0.74 (d, J = 6.3 Hz, 3 H, CH_3), 1.00−1.67 (m, 6 H), 1.71 (s, 3 H, CH_3), 1.81−2.17 (m, 2 H, CH_2CH=C), 3.31−3.52 (m, 2 H, $CH_2CH_2OCH_2$), 4.33 (s, 2 H, OC$H_2C_6H_5$), 5.19 (t, J = 7.4 Hz, 1 H, C=CH), 7.18 (s, 5 H, aryl-H); ^{13}C NMR δ 19.57 (q), 21.22 (q), 24.89 (t), 28.96 (d), 36.29 (t), 37.16 (t), 68.31 (t), 72.91 (t), 127.5 (d), 127.66 (d), 128.32 (d), 128.53 (d), 134.22 (s), 138.45 (s). Spectral characteristics were analogous to those for an authentic sample of **43**.

(*Z*)-[8,8-$^2H_2$]-1-(Benzyloxy)-3,7-dimethyl-6-octen-8-yl Chloride (46). Obtained from **45** (in the same way as **40** was prepared from **39**) as a colorless oil (89%):[67] ^{1}H NMR δ 0.90 (d, J = 6.6 Hz, 3 H, CH_3), 1.10−1.76 (m, 5 H), 1.80 (s, 3 H, CH_3), 1.95−2.21 (m, 2 H, CH_2CH=C), 3.42−3.58 (m, 2 H, CH_2-OCH_2Ph), 4.50 (s, 2 H, OCH_2Ph), 5.36 (m, J = 7.4, 1.4 Hz, 1 H, C=CH), 7.33 (s, 5 H, aryl-H); ^{13}C NMR δ 19.44 (q), 21.47 (q), 25.33 (t), 29.47 (d), 36.59 (t), 36.86 (t), 68.50 (t), 72.91 (t), 127.46 (d), 127.59 (d), 128.32 (d), 130.96 (s), 131.47 (d), 138.60 (s).

(*Z*)-[8,8,8-$^2H_3$]-1-(Benzyloxy)-3,7-dimethyl-6-octene (47). Obtained from **46** on $LiAlD_4$ reduction (in the same way as **41** was prepared from **40**) as a colorless oil (93%):[44] ^{1}H NMR δ 0.89 (d, J = 6.3 Hz, 3 H, CH_3), 1.04−1.76 (m, 5 H), 1.68 (s, 3 H, CH_3), 1.83−2.15 (m, 2 H, CH_2CH=C), 3.43−3.58 (m, 2 H, CH_2OCH_2Ph), 4.50 (s, 2 H, OCH_2Ph), 5.10 (br t, J = 6.6 Hz, 1 H, C=CH), 7.33 (s, 5 H, aryl-H); ^{13}C NMR δ 19.54 (q), 25.45 (t), 25.65 (q), 29.55 (d), 36.70 (t), 37.20 (t), 68.71 (t), 72.90 (t), 124.83 (d), 127.45 (d), 127.60 (d), 128.33 (d), 131.05 (s), 138.68 (s).

(*Z*)-[8,8,8-$^2H_3$]-3,7-Dimethyl-6-octen-1-ol (48). Obtained by deprotection of **47** (in the same manner as **42** was prepared from **41**) as a colorless oil (84%):[44] IR ν(OH) 3620, 3680 cm^{-1}; ^{1}H NMR δ 0.89 (d, J = 6.6 Hz, 3 H, CH_3CH), 1.10−1.61 (m, 6 H), 1.66 (d, J = 1.3 Hz, 3 H, CH=CCD_3CH_3), 1.83−2.10 (m, 2 H, CH_2CH=C), 3.56−3.77 (m, 2 H, CH_2OH), 5.08 (br t, J = 6.9 Hz, 1 H, C=CH); ^{13}C NMR δ 19.46 (q), 25.40 (t), 25.61 (q), 29.11 (d), 37.17 (t), 39.84 (t), 61.12 (t), 124.69 (d), 131.16 (s).

(1*S,3*R**,4*S**)-*p*-Menthane-3,8-diol Carbonate (49a).** To a solution of the *cis*-diol **5a** (500 mg; 2.92 mmol) and pyridine (460 mg) in toluene (10 mL) was added a 20% solution of phosgene in toluene (8.25 mL; 1.93 M; 1.1 equiv) at 0 °C. After 15 min, the reaction mixture was quenched with 1 M HCl, the product was extracted into Et_2O (3 × 50 mL), and the combined organic layers were washed with water, 5% aqueous $NaHCO_3$, and brine and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the solid residue was crystallized from hexane to afford the carbonate **49a** (537 mg; 2.72 mmol; 93%): mp 94−95 °C; IR ν(C=O) 1730 cm^{-1}; ^{1}H NMR δ 0.92 (d, J = 6.5 Hz, 3 H, CH_3CH), 1.05−1.25 (m, 5 H), 1.38 (s, 3 H, *eq*-CH_3), 1.51 (s, 3 H, *ax*-CH_3), 1.55−1.66 (m, 2 H), 2.13 (dd, J = 14.5, 3.0 Hz, 1 H, 2-H), 4.85 (d, J = 2.6 Hz, 1 H, CHO); ^{13}C NMR δ 21.19 (t), 21.52 (q), 25.19 (d), 25.69 (q), 27.96 (q), 32.86 (t), 38.45 (t), 39.07 (d), 74.44 (d), 83.11 (s), 149.63 (s); HRMS (EI) m/z 199.133 41 (calcd for $C_{11}H_{19}O_3$, 199.133 42; MH^+). In the NOE difference experiments, irradiation at 4.85 ppm (CH−O) gave 2% enhancement of the signal at 1.51 ppm (CH_3-axial), while irradiation at 1.51 ppm resulted in 11% enhancement of the signal at 4.85 ppm (CH−O); no enhancement of the latter signal was observed upon irradiation at 1.38 ppm (CH_3-equatorial).

[9,9,9-$^2H_3$]-(1*S,3*R**,4*S**,8*S**)-*p*-Menthane-3,8-diol Carbonate (49b).** Prepared from the diol **5b** (in the same manner as its nonlabeled counterpart **49a**) in 91% yield: IR (CH_2Cl_2) ν 1730 cm^{-1}; ^{1}H NMR δ 0.92 (d, J = 6.6 Hz, 3 H, CH_3CH), 1.05−1.25 (m, 5 H), 1.51 (s, 3 H, CH_3), 1.55−1.66 (m, 2 H), 2.12 (dd, J = 14.5, 3.0 Hz, 1 H, 2-H), 4.85 (d, J = 2.5 Hz, 1 H, CHO); ^{13}C NMR δ 21.23 (t), 21.56 (q), 25.22 (d), 27.91 (q), 32.91 (t), 38.49 (t), 39.12 (d), 74.45 (d), 83.0 (s), 149.67 (s).

(1*S,3*S**,4*S**)-*p*-Menthane-3,8-diol Carbonate (51a).** Obtained from the corresponding diol **4a** (in the same way as **49a** was prepared from **5a**) in 86% yield: IR ν(C=O) 1730 cm^{-1}; ^{1}H NMR δ 0.94 (d, J = 6.6 Hz, 3 H, CH_3CH), 1.08−1.29 (m, 5 H) 1.30 (s, 3 H, *ax*-CH_3), 1.37 (s, 3 H, *eq*-CH_3), 1.65−1.87 (m, 2 H), 2.02−2.19 (m, 1 H), 4.13 (dt, J = 11.0, 4.4 Hz, 1 H, CHO); ^{13}C NMR δ 21.60 (q), 22.50 (q), 24.81 (t), 27.69 (q), 30.64 (d), 33.45 (t), 39.75 (t), 46.07 (d), 76.81 (d), 84.48 (s), 149.03 (s).

[9,9,9-$^2H_3$]-(1*S,3*S**,4*S**,8*S**)-*p*-Menthane-3,8-diol Carbonate (51b).** Obtained from the corresponding diol **4b** (in the same way as **49a** was prepared from **5a**) in 90% yield: IR ν(C=O) 1730 cm^{-1}; ^{1}H NMR δ 0.94 (d, J = 6.6 Hz, 3 H, CH_3-CH), 1.07−1.30 (m, 5 H), 1.37 (s, 3 H, *eq*-CH_3), 1.65−1.87 (m, 2 H), 2.02−2.19 (m, 1 H), 4.13 (dt, J = 11.0, 4.4 Hz, 1 H, CHO); ^{13}C NMR δ 21.70 (q), 24.94 (t), 27.71 (q), 30.79 (d), 33.58 (t), 39.85 (t), 46.18 (d), 76.90 (d), 84.41 (s), 149.14 (s).

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Supporting Information Available: IR, MS, and HRMS spectral characteristics and elemental analyses for the new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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